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A FORTRAN PROGRAM TO CALCULATE AN ENGINEERING ESTIMATE OF THE THERMAL RADIATION TO THE BASE OF A MULTI-ENGINE SPACE VEHICLE AT HIGH ALTITUDES

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ABSTRACT

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The authors wish to express their thanks to Mr. W. K. Dahm for many helpful discussions, and particularly for his suggestions concerning estimation of the flow field in the intersection regions.

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SUMMARY

A method of estimating the radiant heat flux in a base of arbitrary shape from intersection regions caused by the interaction of hydrogen-oxygen engine exhaust jets is presented. An approximate method of generating the intersection region shape and temperature-pressure profiles is discussed. A computer program incorporating both of the above is described and instructions are given for its loading and use. The accuracy of this program is expected to yield within an order of magnitude of the true value of thermal radiation.

I. INTRODUCTION

A contributing factor to the base heating rate on upper stage vehicles is radiation from the exhaust plumes. Limiting the discussion to upper stage vehicles makes it unnecessary to consider the afterburning problem. With this simplification, this radiant heating problem lends itself to division into three distinct radiating regions: the supersonic cores, the first order plume impingement regions, and the extremely complex flow field downstream from the base where the supersonic cores, first order regions, and higher order regions merge. The term "first order plume impingement region" is used to describe the region created by the shock formed when two exhaust plumes intersect. This region is an area of high temperature and pressure. A second order region is formed by the intersection of two first order regions. This terminology can be extended to describe any number of intersecting regions and will be used throughout this report.

Of the three types of radiating regions, the first two yield to analysis while the third, being virtually undefinable, does not. It was decided early in the analysis to consider the supersonic cores and first order regions as independent primary sources of radiation. To take account of the complex downstream flow field, it was decided to estimate a "lump sum" addition to the final overall radiative flux, this estimate being based on the numbers obtained for the primary radiation sources. Further analysis has revealed that of the two remaining regions, the supersonic cores are often insignificant; thus we have limited ourselves in the computer program described here to a calculation of the radiation from the first order intersection regions only.

The supersonic cores in general are at a considerably lower calculated temperature than the intersection region and, in addition, are located closer to the base. Because of this, radiation is less intense and more completely blocked by components in the base region. However, for the user who feels that the supersonic cores will contribute materially to his particular problem, a program has been developed to calculate the additional radiation from these regions using methods identical to those described in this report.

Proper use of the program discussed here will thus provide the user with an estimate of the incident radiation in a minimum of time and will show if a more detailed analysis is needed.

II. CAPABILITIES AND LIMITATIONS

A. Capabilities

The program will estimate the radiation incident on a base of arbitrary configuration from any number of first order regions and will predict how much of this radiation will be blocked by intervening structures in the base region. The user has the option of choosing the method of calculation of the temperature and pressure fields in the intersection region from the three methods programmed. In addition, the actual radiation is calculated by two different methods to allow comparison of two theoretical approaches to the problem. Of these methods, the average temperature and pressure method is more conservative since it assumes that the radiation passes through a transparent space from the radiating region to the base, when in fact it is passing through an absorbing medium. This method thus provides a probable upper limit to the heat flux rate. The other approach accounts for the absorption by an approximate method outlined by Hottel in Reference 1. Each method is presented with and without a blockage correction factor.

B. Limitations and Assumptions

As mentioned earlier, this program computes only the radiation contribution from the first order intersection regions. These regions are assumed to have approximately elliptical cross sections and their temperature and pressure profiles are radially invariant. That is, temperature and pressure are assumed to vary in an axial direction only. These profiles and the geometry of the region are generated from input taken from a method of characteristics printout for a free jet expansion into quiescent air. The flow model for the first order regions is generated by assuming that this expanding plume impinges on a flat plate placed in the flow at a distance equal to one half the distance between nozzle centerlines. Oblique shock theory is then used to produce the geometry as described in Section IIIA of this report.

Both radiation methods use the emissivity data of Hottel given in Reference 1 without the correction for partial pressure. These data are used in the form of a polynomial curve fit with a maximum error in fit of 3 percent. Radiation from each intersection region is assumed to pass through a transparent medium until it impinges on the base or is blocked by one of the solid components in the base region (such as motors and heat shield).

Therefore, the program is restricted to use in cases where the only significant radiating species in the exhaust is water vapor. If the curves were fit to new emissivity data, the program could be changed to treat other radiating species.

III. THEORETICAL BACKGROUND

The gas radiation is treated with a comparatively crude approximation. The emission and absorption coefficients, which actually vary in more or less unknown fashion through the emission spectrum of the gas are replaced by a lumped emissivity representing an integrated effect over the whole emission spectrum. This lumped or total emissivity was obtained from experiments on comparatively small samples of a homogeneous gas and extrapolated versus sample size, pressure, and temperature. The extrapolation becomes progressively more uncertain the further one moves away from the actual test conditions. Use of these data for estimating radiative heating of full scale rocket configurations should normally involve extrapolation of these data to larger beam lengths and lower pressures than those used in the basic experiments. Further, these measurements from homogeneous gas samples are used to estimate radiative emission from nonhomogeneous gas volumes. This may produce additional uncertainties.

Two methods are proposed for this estimate: the average temperature method and the absorption method. In both cases, the radiating gas volume is subdivided into conical pencil-like volume elements, extending along lines of sight from the base surface element in question. Temperature, density, and partial pressure of the radiating species vary along the gas pencil.

For the average temperature method, the properties of the gas, i.e., T^4 and partial pressure, are averaged over the length of the pencil. The "pencil" is then treated as a homogeneous gas sample, yielding a corresponding emissivity with a corresponding view factor. From these, the energy flux contribution that impinges on the base surface element under investigation is computed.

In the absorption method, the "gas pencil" is divided longitudinally into individual elements of different pressures and temperatures. The energy radiated from each longitudinal element toward the base surface element under investigation is subject to absorption losses in the pencil elements it has to pass through. This absorption loss is estimated by the assumption that the whole gas pencil between the radiating element and the surface of the intersection region has the same gas properties (T, P_{H_2O}) as the radiating element. While this model admittedly loses any effects of property variation on the absorption, it significantly reduces the complexity of the estimate by eliminating one integration.

To simplify the presentation, the following discussion will consider the program as though it were divided into four separate programs.

A. Geometry and Temperature-Pressure Profiles

From a method of characteristics analysis of a free plume expansion into quiescent air, one may obtain values for Mach number (M) and flow direction angle (θ) at various points in the exhaust plume. Values of M and θ along a line of constant radius are interpolated from this output (Figure 1). In addition, one obtains the plume expansion radius (radial distance from nozzle centerline to jet boundary streamline) as a function of axial distance. Using these input data, the initial region geometry and temperature-pressure profiles are generated using the following procedure.

1. Geometry of the Intersection Region

In Figure 2, a representative cross section is drawn. The semi-major axis of the cross section, ADIS, was determined by connecting the overlap of circles whose diameters were established by the free plume boundaries from the method of characteristics. Determination of the semi-minor axis was more difficult. It was assumed that the flow field from two adjacent streams deflects by the same amount. This assumption preserves symmetry about the major axis of the region and is compatible with a hypothetical model consisting of a plane placed half way between two adjacent engines. This model is sketched in Figure 3. At points 0, 1, 2, 3, etc., the Mach number and flow angles are known. The flow impinging on the plate at point 0 produces an oblique shock at an angle δ_0 given by the equation

$$\cot \theta = \tan \delta_o \left(\frac{(\gamma + 1) M_1^2}{2 (M_1^2 \sin^2 \theta - 1)} - 1 \right) \qquad (1)$$

where M_1, the Mach number before the shock, is the Mach number M_o which we have obtained from the method of characteristics analysis. This shock is shown as OB-1. It is clear that it is at an angle of $(\delta - \theta)$ from the hypothetical flat plate. The mass flow between streamline SL-0 and SL-1 is now assumed to be turned at the shock so that it is flowing downstream parallel to the wall. Because of continuity, the flow occupies a certain distance from the plate to some streamline SL-1'. Next, the Mach number and flow angle known to exist at point 1 are transferred radially to point 1'. This transfer is justified on the grounds that the temperature and pressure are assumed constant in a radial direction and that thus the flow angle and Mach number must be constant also. At point 1' a new shock angle δ_1 is calculated as before and another section of the intersection region boundary is determined. The process is repeated until the entire region geometry is obtained. It is immediately obvious that this approach ignores mass flowing between point A and point 1'. This assumption should be reasonable if the value of $(\delta - \theta)_o$ is small and the value of $(\theta)_1$ is large. This case corresponds to the highly expanding plume, which is the case normally encountered in high altitude operation.

Equation (1) is limited in that it can only generate shock angles for values of flow angle less than a certain value. Figure 12 shows a parametric plot of this equation for a γ value of 1.23 and for Mach numbers ranging from 1.1 to 20. It is clear that since plume Mach numbers seldom exceed 10, flow angles of 55 degrees and above will not yield solutions to equation (1). In these cases, a shock angle of 65 degrees was assumed since this is approximately the maximum shock angle that can be produced by equation (1) for Mach numbers in the range of those encountered in jet plumes. (Note that there are two solutions to equation (1) for any flow angle. The highest, or "strong shock" solution, is not used in the analysis.)

The process outlined above is repeated until a complete geometrical profile of the region is developed. Figure 4 illustrates the application of the procedure for several increments. Referring to the Figure, we can see that the geometrical relation which links any one radial distance to the preceding radial distance is

$$(B/D)_n = (B/D)_{n-1} + \tan (\delta - \theta)_{n-1} \quad (X/D)_n - (X/D)_{n-1}. \qquad (2)$$

2. Pressure-Temperature Profiles

With the geometry of the intersection region computed, the program returns to the input data. The pressure-temperature profiles are generated using the same model as before. Postulating as before the information of an oblique shock whose angle is determined by the input flow angle for that particular axial distance, the proglem resolves itself into the determination of static temperatures and pressures behind a shock from the total conditions before the shock. Three methods of calculating these temperatures and pressures are programmed and may be selected by the user. In general, the oblique shock temperature and pressure equations should be used since they are more conservative than the other two models and because their use maintains consistency with the equations used to generate the region geometry.

Using the subscripts 1, 2, and 0 to denote, respectively, static conditions before the shock, static conditions after the shock, and total conditions, the following isentropic perfect gas relation holds:

$$\frac{P_1}{P_o} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma}{\gamma-1}} . \tag{3}$$

Also the adiabatic perfect gas relation is

$$\frac{T_1}{T_o} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1} . \tag{4}$$

The oblique shock relations used are taken from NACA Report 1135 as

$$\frac{T_2}{T_1} = \frac{[2\gamma M_1^2 \sin^2 \delta - (\gamma - 1)][(\gamma - 1) M_1^2 \sin^2 \delta + 2]}{(\gamma + 1)^2 M_1^2 \sin^2 \delta} \tag{5}$$

and

$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 \sin^2 \delta - (\gamma - 1)}{\gamma + 1} . \tag{6}$$

As mentioned in the geometry section, cases exist where the shock angle δ cannot be determined. In these situations, the program automatically switches to another method of calculation using the Rankine-Huginot equation

$$T_2 = T_o \left[\frac{(1 + \beta)(1 + \alpha) + \alpha\,(\beta + \beta^2)}{(1 + \frac{\gamma - 1}{2} M_1^2)(1 + \alpha) + \beta + \frac{\gamma - 1}{2} M_1^2\, \beta} \right], \tag{7a}$$

where

$$\alpha = \frac{\gamma - 1}{\gamma + 1} \quad \text{and} \quad \beta = \gamma\, M_1^2 \sin^2 \theta \tag{7b}$$

for the temperature calculation.

For the pressure calculation, the modified Newtonian Impact Theory equation

$$\frac{P_2}{P_1} = C_p\ (\gamma/2)\ M_1^2 + 1 \tag{8}$$

and

$$C_p = 2 \sin^2 \theta \tag{9}$$

is used. These equations may also be called for by the user if desired by inputing a control value as described in Section VIIIA of this report.

In addition, the isentropic flow equation

$$\frac{T_2}{T_1} = \left(C_p\, \frac{\gamma}{2}\, M_1^2 + 1 \right)^{\frac{\gamma - 1}{\gamma}} \tag{10}$$

is programmed and may be requested by use of the control variable. The pressure calculation is made using equation (8).

These calculations are repeated progressing in an axial direction until the entire profile has been generated. Due to the assumption that the static temperature before the shock is constant, it follows that the static temperature behind the shock does not vary from point 0 to point 1' in Figure 3 and thus also from 0 to 1. Then, at point 1, a step discontinuity will exist and the temperature from 1 to 2 will be the temperature calculated from the flow angle at point 1. If a plot of temperature vs axial distance were obtained, these discontinuities would cause the curve to resemble a "step" function. To smooth the curve, linear temperature gradients and not constant temperatures are assumed to exist between analyzed axial points.

B. The Average Temperature Method

The Average Temperature Method is an analysis of the problem which uses the fundamental Stephan-Boltzman Law

$$Q = \sigma T^4. \tag{11}$$

Obviously, a sort of mean temperature and pressure for each radiating increment must be developed. The method of calculating these mean values is described below.

The intersection region was first divided into a number of increments. A line of sight from a point on the base to the lower edge of each increment was established and extended through to the rear face of the plume. A view factor, F, to account for the fact that the point on the base only "sees" one side of each radiating increment, was calculated following the analysis of Sparrow [2]. This derivation is performed in detail in Appendix A. This factor is calculated for each individual increment radiating to a point (Figure 5).

The mean temperature along the beam length itself is

$$T_{AV}^4 = \frac{\int_{x_1}^{x_2} (T(x))^4 \, dx}{x_2 - x_1}, \tag{12}$$

where x_1 and x_2 are the axial coordinates of the points where the beam enters and leaves the intersection region, respectively. A similar formula is applied for the evaluation of the average pressure along the beam length. Using this average pressure, the partial pressure of the water vapor in the exhaust is

$$P_{H_2O} = (FX1)\ P_{AV}, \tag{13}$$

where FX1 is the mole fraction of H_2O vapor in the exhaust plume.

With the partial pressure, temperature, and beam length determined, the emissivity is obtained from the data of Hottel [1]. These emissivity data have been curve-fitted with a series of polynomial expressions such that the maximum error is ±3 percent in fit. From this the emissivity may be determined and used in the final expression for Q, the heat flux

$$Q = \sigma F \epsilon \ T_{AV}^4. \tag{14}$$

C. The Absorption Method

The absorption method employs the equation developed by Hottel [1] to account for the absorption in the intersection region. The equation employed is

$$Q = \frac{1}{\pi} \int_{\omega} \int_{X} \sigma\, T^4\, (d\epsilon/dX) \cos\theta d\omega\ \ dX. \tag{15}$$

In this expression, X is the optical beam length and is evaluated as

$$X = P_{H_2O}(L), \tag{16}$$

and

$$\frac{1}{\pi} \int_{\omega} \cos \theta d\omega \tag{17}$$

is a solid angle shape factor previously called F. Then

$$Q = F\sigma \int_{P_W L} T^4 \frac{d\epsilon}{d(PL)} d(PL). \tag{18}$$

The plume is divided as before into increments and a pencil ray (line of sight) erected to the lower edge of each increment. This line of sight is now the optical beam along which equation (18) must be evaluated. To do this, we must first evaluate the pressure and temperature at various points along the beam. This is done using a straight line interpolation method which is quite valid because of the smooth nature of the temperature and pressure profiles and to the small distance between points at which the evaluation is made.

The emissivity slope is easily evaluated since the curve fits mentioned in Section IIIB are functions of (PL) with T as a parameter. Thus, an explicit differentiation of these polynomial curve fits is possible without resorting to numerical techniques. Since all the variables are functions of the position variable L, we may now proceed to simplify equation (18).

$$Q = F\sigma \int_{PL_1}^{PL_2} T_1{}^4 (1/P) \frac{d\epsilon}{dL} PdL, \tag{19}$$

since

$$d(PL) = PdL \tag{20}$$

by the assumption that temperature and pressure are constant in the particular increment of length under analysis. Then

$$Q = F\sigma \int_{PL_1}^{PL_2} T_1^{\,4} \frac{d\epsilon}{dL}\, dL. \tag{21}$$

Equation (21) is evaluated using Simpson's rule and the value for F already computed in Section IIIB.

D. Blockage

In certain base configurations, a great deal of the radiation from the exhaust plumes will impinge upon the motors, heat shield, and other obstructions in the base, and will not therefore contribute to the heat flux rate to the base. To evaluate how much of the radiation is blocked, a section of the program generates a blockage factor and applies it to each intersection region. This blockage factor is not related to the form factor F computed in Section IIIB. The form factor expresses what portion of the intersection region the point "sees" assuming a transparent space between radiating region and point. The blockage factor increases the realism of the model by removing the "transparent space" assumption and substituting the actual base obstructions.

It was decided that the easiest method of generating a blockage factor was to determine if each individual beam was blocked and if it were to consider the radiation from the increment associated with that beam to be 0. Since the increments have widths which in some cases are appreciable, three lines of sight are erected to each increment, one to each side and one to the center. Each line is assumed to represent one-third of the radiation incident from the region. Thus, blockage of each beam reduces the incident radiation by one-third.

The obstructions are first represented as circles in a three-dimensional, Cartesian coordinate system located as follows.

1. The xy plane is located at the exit plane of the motors such that the z coordinates of all obstructions and the points to be analyzed are negative or zero.

2. The xz plane passes through the center of the heat shield and through the point being analyzed with the negative axis in the direction of the point being analyzed such that "x" and "z" coordinates of the point are negative and the "y" coordinate is always 0.

3. The yz plane is oriented as usual in a right-handed Cartesian coordinate system. See Figure 6 for a graphical illustration of this system.

The obstructions are assumed to be circles located in, or parallel to, the xy plane. In this way, a three-dimensional nozzle can be fairly well represented by, for example, three circles with radii equaling the radii of the nozzle at three different heights. The model expressing this nozzle would then become three circular areas in space given by the relations (in our coordinate system)

$$(x - h)^2 + (y - k)^2 \leqq r_1^2 \qquad z = z_1 \tag{22}$$

$$(x - h)^2 + (y - k)^2 \leqq r_2^2 \qquad z = z_2 \tag{23}$$

$$(x - h)^2 + (y - k)^2 \leqq r_3^2 \qquad z = z_3. \tag{24}$$

If the obstruction has its axis parallel to the axis of the vehicle (which is our z-axis) then "h" and "k" are constant for the three equations. The "h" and "k" coordinates are the "x" and "y" coordinates of the center of the obstruction. If the axis of the body is tilted with respect to the vehicle axis then "h" and "k" vary. They are then the coordinates of the center of the obstruction at that particular height. A slight error is thus introduced because of the assumption that the circles lie parallel to the xy plane when, in fact, they are tilted to be perpendicular to the obstruction axis; but this error will not be appreciable unless the tilt is considerable.

With equations (22), (23), and (24) defining three areas in space, it is clear that, for a line of sight to avoid intersecting one of these areas, yet in fact to be blocked by the nozzle, the line of sight must be almost parallel to the xy plane. Since in practice the intersection region must begin at some finite distance above the nozzle exit plane, and the point to be analyzed must be some distance below the nozzle exit plane, the line of sight angle should be sufficient to allow these three circles to adequately describe the blockage. In many cases, in fact, one circle suffices. (In theory, a large number of circles used as above could completely describe an axisymmetric obstruction. In practice, however, only forty equations may be used in the program

to describe the whole base or a portion of it if so desired. Therefore, one should not use more circles than are necessary on any one obstruction.)

Once the entire base picture has been presented in the simplified terms shown above, the coordinate system is shifted so that it is now centered at the point to be analyzed, the orientation of the axes being as before. Now it is clear that all the obstructions are at positive "z" coordinates and most are also at positive "x" coordinates.

To illustrate this transformation, assume a point P located at (x', 0, z') as shown in Figure 6 where z = 0 is defined to exist at the nozzle exit plane. Assume also a point in an intersection region located at (x_i, y_i). Its z coordinate is unimportant. Assume also a circular blockage located at (h, k, z_o) with a radius "r." The equations for this blockage region are

$$(x - h^2) + (y - k)^2 \leq r^2. \qquad z = z_o \tag{25}$$

To transfer these equations to a coordinate system centered at P, the following transformation equations are needed. (The subscript 2 refers to the new system.)

$$x_2 = x - x' \qquad y_2 = y \qquad z_2 = z - z'. \tag{26}$$

Then, the transformed blockage equation is

$$(x_2 + x' - h)^2 + (y - k)^2 \leq r^2 \qquad z_2 = z_o - z'. \tag{27}$$

Given a line of sight with an angle, β, from the horizontal (the new xy plane) and knowing the z coordinate of the obstruction (Figure 7), we may calculate the distance (HYP) from P to the point where the line of sight passes through the plane of the obstruction ($z_2 = z_o - z'$).

$$HYP = \frac{z_2}{\tan(\beta)}\ . \tag{28}$$

Also, from the coordinates of the center of the intersection region which must be crossed by the beam, an angle θ may be calculated as follows:

$$\theta = \tan \frac{|y_i|}{x_i} . \tag{29}$$

With θ and HYP, the coordinates of the point where the line of sight passes through the intersection region may be calculated.

$$x_o = (\cos\ \theta)\ \mathrm{HYP} \tag{30}$$

$$y_o = (\sin\ \theta)\ \mathrm{HYP}. \tag{31}$$

The sign of y_o is the same as the sign of y_i since P is on the x-axis.

Now, if the calculated values of x_o and y_o satisfy equation (25) the line of sight is blocked. If not, the process is repeated with new parameters. Finally, a new summation of all the unblocked radiation is made to give a better estimate of the environment.

IV. PROGRAM DESCRIPTION

The program is written in Chain Fortran for the GE 225 computer. The use of Chains was caused by the large number of subscripted variables and makes the program a compendium of four smaller programs. Each of these smaller programs contains the coding of the equations contained in one of the four sections just discussed.

This segmenting makes checkout and error investigation quite simple since one can immediately isolate a given section as the one in which the error occurred and restrict his investigation to it.

Each of the four sections follows closely the pattern laid down in the preceding portion of this report. Numerous interpolation, approximation, and averaging methods which are similar to techniques developed in the standard texts [3] are used as needed in the program. No unusual numerical differentiation and integration techniques are employed, and nothing other than simple geometry is used in the various form factor and beam length calculations. In short, the theory presented in the preceding portion of this report is followed closely with little modification.

Figure 8 contains a printout of the program as it is read into the machine. Notice the marginal notations separating the four sections of the program. If each of these sections is compared with the corresponding theory section of this report by a person familiar with Fortran II, there is no reason why he should not be able to follow the programming and to verify his results in any way he wishes.

Figure 9 contains a flow diagram to completely illustrate the flow of control throughout the program.

V. NOTATION

Program Symbol		Description and Units
(J) (or a similar subscript)		Numerical subscript where J has a value from one number to another (i.e., 1 to L).
A(I, J) (J = 1 to 4)		Table of input from the method of characteristics.
A(I, 1)	CHAIN I	Distance, nondimensionalized by DIA, measured along the nozzle axial line from the exit plane of that nozzle. The first value must be the initial intersection point.
A(I, 2)	CHAIN I	Mach number corresponding to A(I, 1) but located on the axial line of the intersecting region (not to be confused with critical condition Mach number, M*).
A(I, 3)	CHAIN I	Flow direction angle corresponding to A(I, 1) but located on the axial line of the intersecting region, in radians.
A(I, 4)	CHAIN I	Radius, nondimensionalized by DIA, of the circle formed by a plane drawn perpendicular to the nozzle axial line and cutting the exhaust plume for a corresponding A(I, 1).

Program Symbol		Description and Units
A(I, 1) A(I, 2) A(I, 3) A(I, 4)	CHAIN IV	Center and radii of the blockage regions located in the (x, y, z) coordinate system illustrated in Figure 6, ft.
ABSIS		An increment length, nondimensionalized by DIA, that is 1/50 that of the beam length, FLE(J).
ADIS(J)		One-half the length, nondimensionalized by DIA, of the major axis of the elliptical plane for the intersecting region.
ANGLE(J)		The angle formed by the beam and its projection in the base plane, radians.
AVTEM(J)		Average temperature for the beam length, FLE(J), °R.
AVP(J)		Average pressure for the beam length, FLE(J), ATM.
BDIS(J)		One-half the length, nondimensionalized by DIA, of the minor axis of the elliptical plane for the intersecting region.
BLED(J)		Dimensional value for the beam length, ft.
C		The angular difference between the shock angle, DELTA, and a corresponding flow direction angle), radians.
DELI		Minimum shock angle for a given GAMMA and Mach number, FM(J) (zero flow direction angle), radians.
DELM		Maximum shock angle for a given GAMMA and Mach number, FM(J), radians.

Program Symbol	Description and Units
DELTA	Shock angle for a given GAMMA, Mach number, FM(J), and flow direction, T(J), radians.
DIA	Diameter of the nozzle exit, ft.
EMIS	Emissivity of the beam length, FLE(J).
F	Shape factor corresponding to a given beam. (F is the view factor associated with each beam length that radiates energy back to the viewpoint.)
FINTX	x-coordinate of intersection region center in coordinate system of Figure 6.
FINTY	y-coordinate of intersection region center in coordinate system of Figure 6.
FK	The distance, nondimensionalized by DIA, in the base plane from the point of view to the axial line for the intersecting region. (The value of FK is always negative.)
FLAG	Value, either +1 or 0, instructing computer on how to proceed.
FLE(J)	Length, nondimensionalized by DIA, of the beam within the bounds of the intersecting region.
FM(J)	Mach number on the axial line of the intersecting region corresponding to XD(J) (not to be confused with critical condition Mach number, M*).
FXI	Mole fraction of each of the gas components in the exhaust plume.
GAMMA	Ratio of specific heats for the exhaust components.
L	Number of desired data values for XD(J).
LL	Number of data values input for each A(I, 1), A(I, 2), A(I, 3), and A(I, 4) in Chain I.
LLLL	Number of blockage region circles.

Program Symbol	Description and Units
MCON	If +1: oblique shock theory temperature and pressure used. 0: Rankine-Huginot temperature and Newtonian impact theory pressure used. -1: isentropic temperature and Newtonian impact theory used.
PBPX	Ratio of base pressure to exit pressure.
PHI	View angle formed by one-half the minor axis, BDIS(J), of the elliptical plane for the intersecting region and a corresponding projection of part of the beam into the same elliptical plane (Figure 6), radians.
PH2O	Partial pressure for the beam length, FLE(J), ATM.
PO	Chamber pressure of the nozzle, ATM.
P(J) and PW	Static pressure for a location in the exhaust plume, ATM.
PX	x-coordinate of point being analyzed in coordinate system of Figure 5.
PY	y-coordinate of point being analyzed.
PZ	z-coordinate of point being analyzed.
QRAD	Radiant heat flux by the average temperature and pressure method for the beam length, FLE(J), BTU/ft^2-sec.
QRADS	The total accumulated heat flux contribution by average temperature and pressure method for two or more beam lengths, BTU/ft^2-sec.
QRDA	Radiant heat flux by absorption method for a single beam length, FLE(J), BTU/ft^2-sec.
QRDAS	Total accumulated radiant heat flux by absorption method for two or more beam lengths, BTU/ft^2-sec.
R	One-half the distance, nondimensionalized by DIA, between two adjacent nozzle center lines.

Program Symbol	Description and Units
RC(J)	One-half the length, nondimensionalized by DIA, of an axis in the elliptical plane for the intersecting region that is formed by a beam where it pierces this region and a point on the axial line of the same region.
RD(J)	Radius, nondimensionalized by DIA, measured in the same manner as that of A(1, 4) and corresponding to XD(J).
SABSIS	Total accumulated ABSIS increments to point in question.
SSF	The total accumulated shape factor for two or more beam lengths.
SXD	Perpendicular distance, nondimensionalized by DIA, between the base plane and the nozzle exit plane.
TAB	Table of flow direction angles, radians, obtained from a plot of flow direction angle, shock angle, and Mach number (Figure 13).
TABL	Table of Mach number values obtained from a plot of flow direction angle, shock angle, and Mach number (Figure 13).
TDIS(J)	One-half the length, nondimensionalized by DIA, of an axis perpendicular to RC(J) and in the same elliptical plane for the intersecting region.
TEMP(J) and TW	Static temperature for a location in the exhaust plume, °R.
THETA	Flow direction for a given GAMMA, Mach number, FM(J), and shock angle, DELTA, radians.
T(J)	Flow direction angle on the axial line of the intersecting region corresponding to XD(J), radians.
TO	Chamber temperature of the nozzle, °R.

Program Symbol	Description and Units
XD(J)	Arbitrary distance, nondimensionalized by DIA, that is measured in the same manner as is A(I, 1). (Simply numbered values for XD(J) make it easier for the user to plot the results. XD(J) can be set equal to A(I, 1) if so desired.)
XD(L + 1)	Selected value, nondimensionalized by DIA, that is slightly larger than the last input value for XD(J). (The value, XD(L + 1), is necessary so that the solution of shape factor can be completed for the last increment.)
XO	x-coordinate of point at which line of sight to I.R. pierces plane of obstruction.
YO	y-coordinate of point at which line of sight to I.R. pierces plane of obstruction.
ZO	z-coordinate of point at which line of sight pierces plane of obstruction.

VI. INPUT

The program requires as input certain characteristics of the rocket engines on the missile in question, the base geometry and a flow field. Since the input required is quite extensive, it will be treated as three separate topics. In addition, the discussion will be restricted to the input and how it is obtained leaving the actual load format for a separate section.

A. Flow Field Description

The program requires extensive input data to describe the downstream flow field. This input is received in the form of tables of the free exhaust plume properties, Mach number, M, flow angle, θ, and plume radius, R, as functions of axial distance. The axial distance and the plume radius are nondimensionalized by the exit diameter and will hereafter be referred to by their symbolic names X/D and R/D. The Mach number is not the characteristic Mach number M^* but is related to it by

$$M = \sqrt{\frac{2M^{*2}}{(\gamma + 1) - (\gamma - 1)\, M^{*2}}} . \tag{32}$$

The angle θ is expressed in radians. These tables are obtained from a method of characteristics analysis as follows.

In Figure 1 it may be seen that by a two-way interpolation into the method of characteristics output, values of M and θ may be found along a line of given radial distance from the nozzle centerline. In addition, at the specific X/D location at which the M and θ's are found, the free plume radius must also be input as shown in the figure. The first X/D chosen must be at the initial intersection point and additional X/D's down the plume may be chosen arbitrarily; however, the bottom number must not exceed 60.

Given now this set of tables of M, θ, and R/D as functions of X/D, the user next inputs the X/D distances at which he wants his lines of sight to pierce the intersection region. The input fixes the number of increments into which the intersection region will be divided; thus, it will generally be advantageous to input as many as practical. The number of these points is in no way related to the number of points in the above tables except that no more than 60 may be input, and the highest and lowest value must be within the range of the previously input tables.

A review of the oblique shock equations will show that the equation relating the shock angle δ to the flow direction angle θ does not allow a δ to exist for all θ values. In particular, for a given specific heat ratio and Mach number, there exists a maximum θ beyond which a corresponding shock angle does not exist. The program is made aware of these limits by inputting a table of Mach numbers and the corresponding maximum θ values so that it will not try to solve for a nonexistent angle. This table consists of ten values and must be obtained for the correct specific heat ratio as it varies strongly with that parameter.

B. Rocket Motor Input

The given rocket motor must be characterized for the program by inputting its total temperature, total pressure, its exit diameter, the specific heat ratio of its exhaust gases and the pressure ratio (exit pressure to ambient pressure) at which the method of characteristics analysis was run.

C. Base Geometry

Referring to Figure 10, the program needs the distances SXD and FK, both in the nondimensionalized (divided by the exit diameter) mode. In addition, the location of the blockage regions and intersection

regions in a coordinate system oriented as described in Section IIID are needed. The dimensions of this coordinate system must be in feet.

In addition to the above input, a number of constants which effect control of the execution cycle are needed and are described later in the load format section.

VII. OUTPUT

The output is limited since execution time is already quite long and excessive print statements only make it longer. As may be seen in Figure 11, the output is arranged in the same logical order as was followed in Section III. The first section is devoted to the temperature and pressure profiles; the second to one radiation method; the third to the absorption method; and the fourth to the blockage correction factors. As may be seen, the total cumulative radiation, as well as the radiation from the individual increments, is summed in each case.

Note that in the blockage correction section each increment is divided into left, middle and right sides. The coordinates at which the line of sight to each of these three points pierces the planes of the various obstructions (x_o, y_o) are printed out. If the line of sight is blocked, the last set of x_o, y_o coordinates printed out are within a blockage circle. This is shown on the output in Figure 11.

Figure 11 contains the complete output for the sample problem in Section VIIIB.

VIII. LOAD FORMAT AND SAMPLE PROBLEM

A. Load Format

A few basic rules for writing a load format for the GE 225 Fortran are as follows:

1. Fixed point numbers must have an X before the number and must be immediately followed by a comma (i.e., X31,). "X31 ," will be misinterpreted.

2. Each value must be separated by a comma (i.e., .21, .2646, ...).

3. Every data card must end with an asterisk (i.e., .28, .29, .30*).

4. Floating point numbers can be written either in decimal form without exponent or with exponent (i.e., .000539 or 5.39E-4).

5. Any one data card cannot contain values listed on more than one read statement (RCD).

6. Data must be set up in the same order as it is listed in the read statement (RCD).

7. All floating point numbers must have decimal points (i.e., the expression 31 is not permitted).

These rules must be followed explicitly.

In the following discussion the input will be separated into blocks. Each block of data must go on one or more cards. The first item in each new block must be the first item on a new card; i.e., no card may contain data from two blocks.

a. Block 1

(1) A fixed point number expressing the number of values in the input table of M vs X/D. This number is of course also the number of values in the θ vs X/D table and the R/D vs X/D table and must not exceed 60.

(2) A fixed point number giving the number of X/D locations at which the user desires to increment his intersection region.

(3) A fixed point number with its value determined from the following.

(a) X + 1 if oblique shock relations are desired in the solution of the temperature and pressure profiles.

(b) X + 0 if Rankine-Huginot relations are desired.

(c) X - 1 if isentropic flow relations are needed.

(4) A floating point number giving one-half the distance between the centerlines of the two motors which are generating the intersection region. This number is the actual distance nondimensionalized by the exit diameter of the motor.

(5) The value of the chamber total pressure; atmospheres ~ floating point.

(6) The value of the chamber total temperature; °R ~ floating ~~point~~.

(7) The exhaust gas specific heat ratio; floating point.

b. <u>Block 2</u>

A floating point number expressing the base pressure to exit pressure ratio for which the method of characteristics run was made.

c. <u>Block 3</u>

A set of floating point numbers in ascending order expressing the X/D coordinates of the points at which the M and θ will be given.

d. <u>Block 4</u>

A set of floating point numbers expressing the Mach numbers corresponding to the X/D locations given in Block 3.

e. <u>Block 5</u>

A set of floating point numbers giving the corresponding θ values; radians.

f. <u>Block 6</u>

A set of floating point numbers giving the corresponding R/D's. (Note: Together Blocks 3, 4, 5, and 6 give the columns of a table into which the machine may go to interpolate the value of any parameter (M, θ, R/D) at any given X/D value during later execution stages. As a result, extreme care must be taken to assure that proper correspondence is maintained between the elements in the columns.)

g. <u>Block 7</u>

A series of floating point numbers giving the X/D locations at which the plume is desired to be incremented. The number of these points is given in Block 1, part 2.

h. <u>Block 8 and Block 9</u>

These two blocks contain the maximum values of M and θ, respectively, which are used to prevent the program from solving for a nonexistent shock angle. Referring to Figure 12, notice that for a Mach number 4.0 and a flow angle θ of 55 degrees no shock angle δ exists. Thus, to prevent the program from attempting to solve for shock angles

in cases like this, a table of Mach numbers and the maximum corresponding θ angles is input. Figure 12 shows such a table for Figure 12. This table must have ten values.

i. Block 10

(1) Exit diameter of the rocket engines used on the base being considered. A floating point number ~ feet.

(2) The percent water vapor in the exhaust plumes. Floating point ~ dimensionless.

(3) A selected X/D location equal to the last X/D location in Block 7 plus .1. Floating point ~ nondimensionalized.

j. Block 11

(1) The distance in the plane of the point being analyzed from the point of view to the axial line of the intersecting region. This value is always given a negative sign. A floating point number ~ nondimensionalized (see Figure 10).

(2) The angle formed by the semi-major axis, BDIS(J), of the elliptical plane for the intersection region and a corresponding projection of part of the beam into the same elliptical plane. A floating point number ~ radians (see Figure 14).

(3) The perpendicular distance between the plane of the point being analyzed and the nozzle exit plane. A floating point number ~ nondimensionalized (see Figure 10).

k. Block 12

(1) The number of blockage circles being considered. Must not exceed 40. A fixed point number ~ dimensionless.

(2) The x-coordinate of the center of the intersection region being considered. A floating point number (including sign) ~ feet.

(3) The y-coordinate of the center of the intersection region being considered. A floating point signed number ~ feet.

l. Block 13

A series of numbers expressing the x-coordinates of the blockage circle centers. Floating point signed numbers ~ feet.

m. Block 14

A series of numbers expressing the y-coordinate of the blockage circle centers. Floating point signed numbers ~ feet.

n. Block 15

A series of numbers expressing the z-coordinate of the blockage circle centers. Floating point signed number ~ feet.

o. Block 16

A series of numbers expressing the radius of each of the blockage circles. A floating point number ~ feet.

p. Block 17

(1) A value, either +1.0 or 0.0 depending upon whether a new intersection region is to be analyzed next or just a new point. This number is a command to the machine.

+1.0 if a new point is to be analyzed or if this is the last piece of data.

0.0 if a new intersection region is to be considered.

(2) This value is +1.0 if the intersection region being analyzed has an x-coordinate greater than the x-coordinate of the point being considered. If the intersection region has an x-coordinate less than the point being considered, then the value in this position is the x-coordinate. A floating point negative (all x-coordinates are negative according to the defined coordinate system in Section IIID) number ~ feet. As clarification, a case where the x-coordinate must be input in this manner is illustrated in Figure 15.

B. Sample Problem

As a sample problem an analysis of the radiation incident on a point on the thrust structure of the S-II stage from two of the eight I.R.'s will be made. Figure 16 shows the base with some of the necessary geometrical input. Figure 17 shows the same base drawn in the necessary coordinate system to input the coordinates of the intersection regions and blockage regions. Other necessary input data concerning the engine and other features of the base are:

Chamber Total Pressure: 43.004899 atmospheres.

Chamber Total Temperature: 5760 °R

Exit Diameter: 6.6666 feet

Distance between Engine Centerlines: 12.37 feet

Specific Heat Ratio of Exhaust Gases: 1.23

Percent Water Vapor in Exhaust Gases: 63% = .63.

Now a method of characteristics analysis of a J-2 engine free plume expansion into quiescent air must be obtained. From this we develop the following table.

TABLE I

(Note that the axial distance and radius have already been divided through by the exit diameter, 6.6666 ft.)

A X/D	B M	C Theta - θ	D Free Plume Expansion Radius - R/D
.55300	5.55	.59932	.932
.60577	5.678	.61166	.971
.68793	6.121	.69823	1.022
.75513	6.027	.65766	1.062
.82400	6.01	.63600	1.103
.87308	5.89	.60129	1.131
.91254	5.874	.58471	1.456

A X/D	B M	C Theta - θ	D Free Plume Expansion Radius (R/D)
.96408	5.840	.56404	1.182
1.05794	5.80	.53164	1.242
1.09118	5.78	.51986	1.260
1.14699	5.75	.50391	1.292
1.20885	5.723	.48549	1.323
1.27162	5.715	.46950	1.355
1.33487	5.710	.45436	1.388
1.43185	5.69	.43380	1.437
1.52983	5.69	.41471	1.488
1.68460	5.69	.38945	1.561
1.79133	5.70	.37429	1.609
1.90591	5.705	.36038	1.660
2.00453	5.705	.34923	1.710
2.10755	5.715	.33942	1.743
2.20516	5.718	.33107	1.783
2.31099	5.718	.32418	1.825
2.39077	5.716	.32047	1.851
2.40765	5.701	.32655	1.862
2.51795	5.705	.32794	1.902
2.6743	5.717	.31689	1.955
2.82225	5.72	.30810	2.005
2.96077	5.722	.30217	2.050
3.08055	5.725	.29927	2.086
3.19207	5.719	.29961	2.117
3.35044	5.685	.31006	2.165

It has been decided to break up the plume into increments at the following X/D locations:

.56, .60, .7, .8, .9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.6, 2.8, 3.0, 3.2, and 3.3.

In addition, the graph shown in Figure 12 has been made and the values shown in Figure 13 have been chosen as the maximum Thetas and Mach numbers. With this data, the first part of the program may be loaded.

1. <u>Block 1</u>

   a. There are 32 figures in each column of Table I. The value loaded here is X32.

   b. According to the X/D locations shown above, the region is to be incremented at 25 X/D's. Value loaded is X25.

   c. Oblique shock theory is desired. X + 1.

   d. One half the distance between rocket engine centerlines divided by the exit diameter is .92773.

   e. Value is 43.004899.

   f. Value is 5760.0.

   g. Value is 1.23.

2. <u>Block 2</u>

   The pressure ratio for this run was .0185.

3. <u>Block 3</u>

   Load here column A of Table I in order going down, taking as many cards as needed.

4. <u>Block 4</u>

   Load here column B.

5. Block 5

Load here column C.

6. Block 6

Load here column D.

7. Block 7

Load here the 25 values of X/D locations listed on page 28.

8. Block 8

Load here column A of Figure 13.

9. Block 9

Load here column B of Figure 13.

10. Block 10

a. The exit diameter of the engine is 6.666 feet.

b. Value is .63.

c. Since the last value in column A of the input table is 3.35044, the value loaded here is 3.45044.

11. Block 11

a. Referring to Figure 16 and remembering to non-dimensionalize by division by the exit diameter, the value loaded here is - .81404.

b. From the same figure, the value (in radians) loaded is 1.57079.

c. Value here is 2.09559.

Now another table is made. Referring to Figure 17, locate the blockage regions (which are the heat shield and the five motors) and prepare the following table.

TABLE II

Blockage	x-coordinate	y-coordinate	z-coordinate	Radius
	A	B	C	D
Heat Shield	0.0	0.0	-3.4	10.25
Engine I	-6.19	6.19	0.0	3.33
Engine II	6.19	6.19	0.0	3.33
Engine III	6.19	-6.19	0.0	3.33
Engine IV	-6.19	-6.19	0.0	3.33
Engine V	0.0	0.0	0.0	3.33

Also it is noted that the intersection region is located at X = -6.19, y = 0.0. Now this new data is loaded.

12. Block 12

    a. There are six blockage regions so X6 is loaded here.

    b. -6.19 is the value as noted above.

    c. 0.0 is loaded here.

13. Block 13

    Load here column A of Table II.

14. Block 14

    Load here column B of Table II.

15. Block 15

    Load here column C of Table II.

16. Block 16

    Load here column D of Table II.

17. Block 17

    a. Since a new intersection region is to be analyzed the first tendency would be to load 0.0 in this place.

However, it is apparent that actually the new intersection region is formed by two motors separated by the same distance as before and formed by engines with the same characteristics as before. Thus, in effect the same intersection region is being analyzed but from a different point. 1.0 is input here. This tells the machine that it need not calculate new temperature and pressure profiles and that it may start execution with Chain II instead of Chain I.

b. 1.0 is input here because clearly the intersection region is at a larger x-coordinate than is the point.

The input for the first intersection region analysis is now complete. Directly behind it the data for the second intersection region is loaded. Of course, since the machine already has in memory the necessary intersection region data, Blocks 1 through 9 need not be input again. Starting with Block 10 and proceeding in the same manner as before the following is loaded:

18. <u>Block 10</u>

    a. 6.6667

    b. .63

    c. 3.35044.

19. <u>Block 11</u>

    a. - 1.97363

    b. .4895

    c. 2.09559.

20. <u>Block 12</u>

    a. X6

    b. 0.0

    c. +6.19.

21. Block 13

Column A, Table II.

22. Block 14

Column B, Table II.

23. Block 15

Column C, Table II.

24. Block 16

Column D, Table II.

25. Block 17

a. Load here now 1.0. The machine will continue to execute, will try to read data for Block 10 and finding none, will stop.

b. 1.0.

Figure 18 presents the input for this problem as it appears on the input cards.

IX. CONCLUSIONS AND RECOMMENDATIONS

1. This program may be used to estimate radiant heat flux rates to various missile bases from intersection regions produced by H_2-O_2 engines.

2. Possible inaccuracies can exist in the calculated intersection region properties, the emissivity data, or in the application of equation (15).

3. Other inaccuracies arise because of the fact that second and higher order intersections are ignored, radiation from plume to plume is ignored, and blockage by intervening gas masses is ignored.

4. Further work is needed in all the areas mentioned in 2 and 3 above. In particular, an accurate method to calculate the region properties and an accurate method of accounting for second order regions is essential before accurate estimates can be made.

5. Measurements, preferably inflight, must be made before these analytical approaches can be completely trusted. Instrumentation must be developed that will measure these low transient heat flux rates.

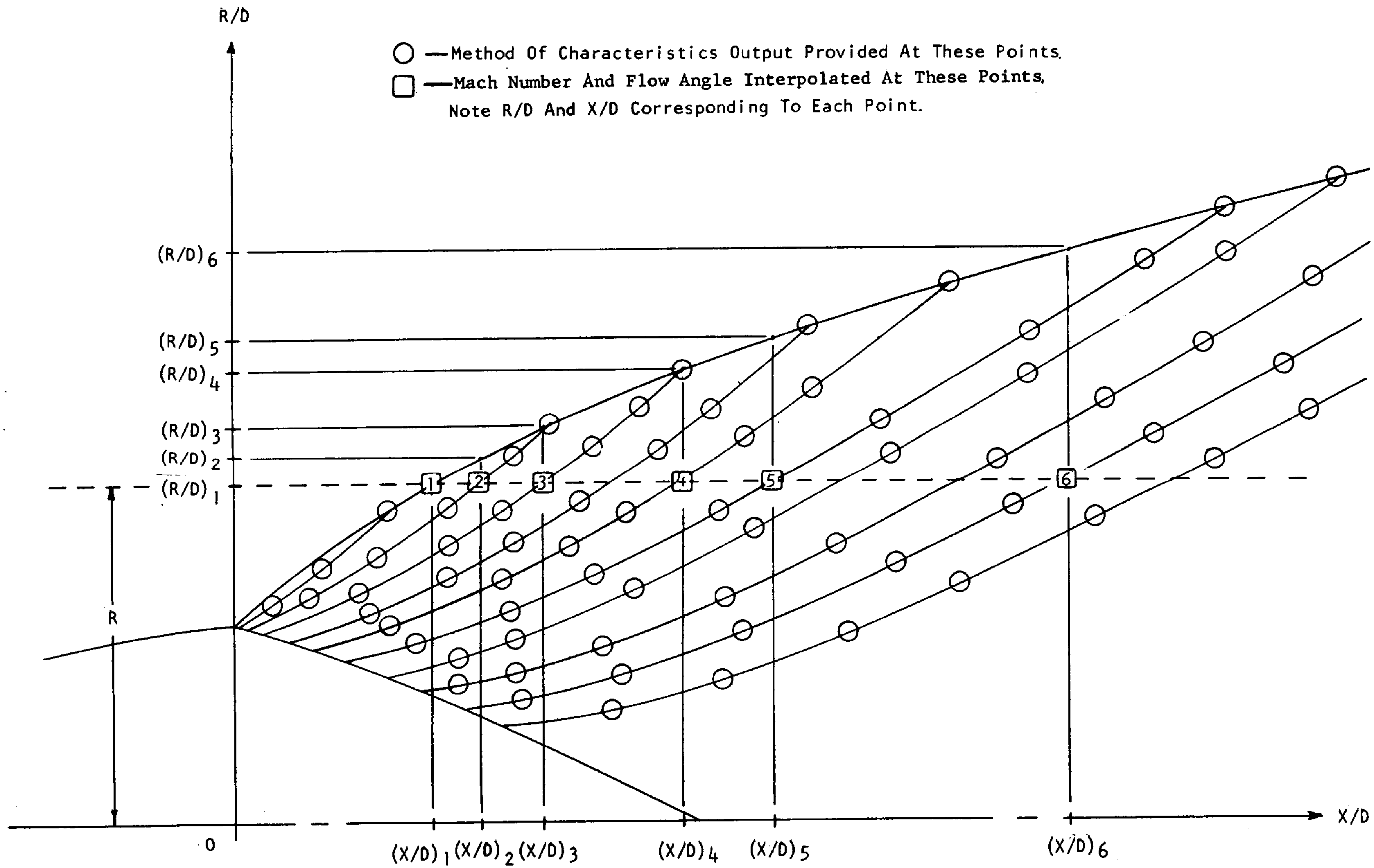


FIGURE 1. INTERPOLATED MACH NUMBER (M) AND FLOW DIRECTION ANGLE (θ) ALONG A LINE OF CONSTANT RADIUS WITHIN THE EXHAUST PLUME

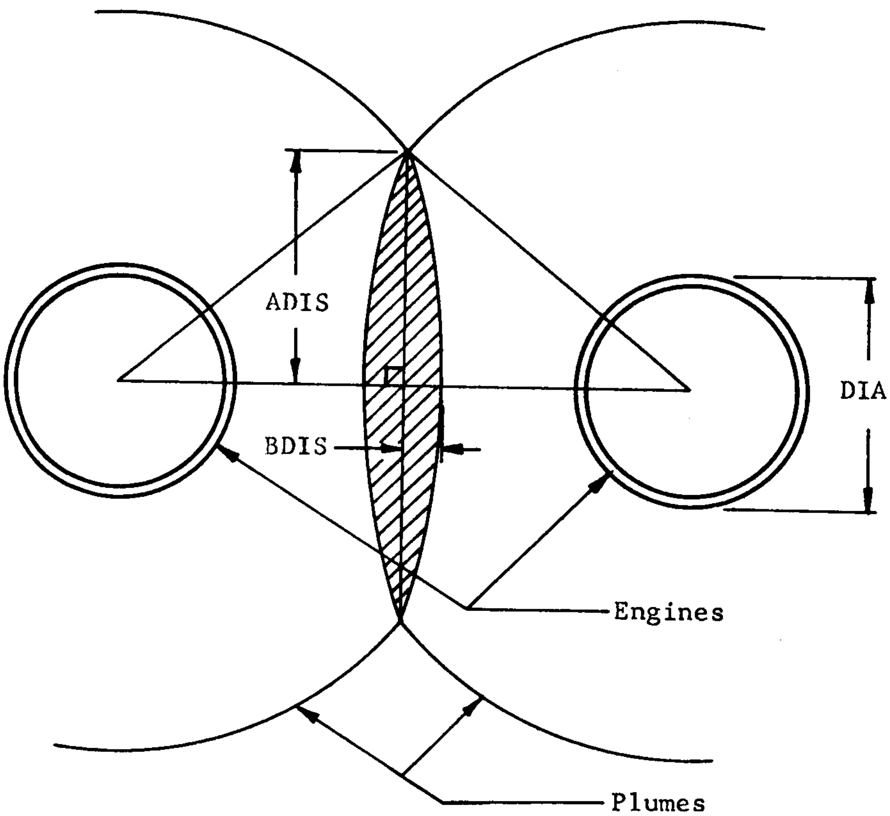


FIGURE 2. GEOMETRY OF THE CROSS SECTION OF THE INTERSECTION REGION

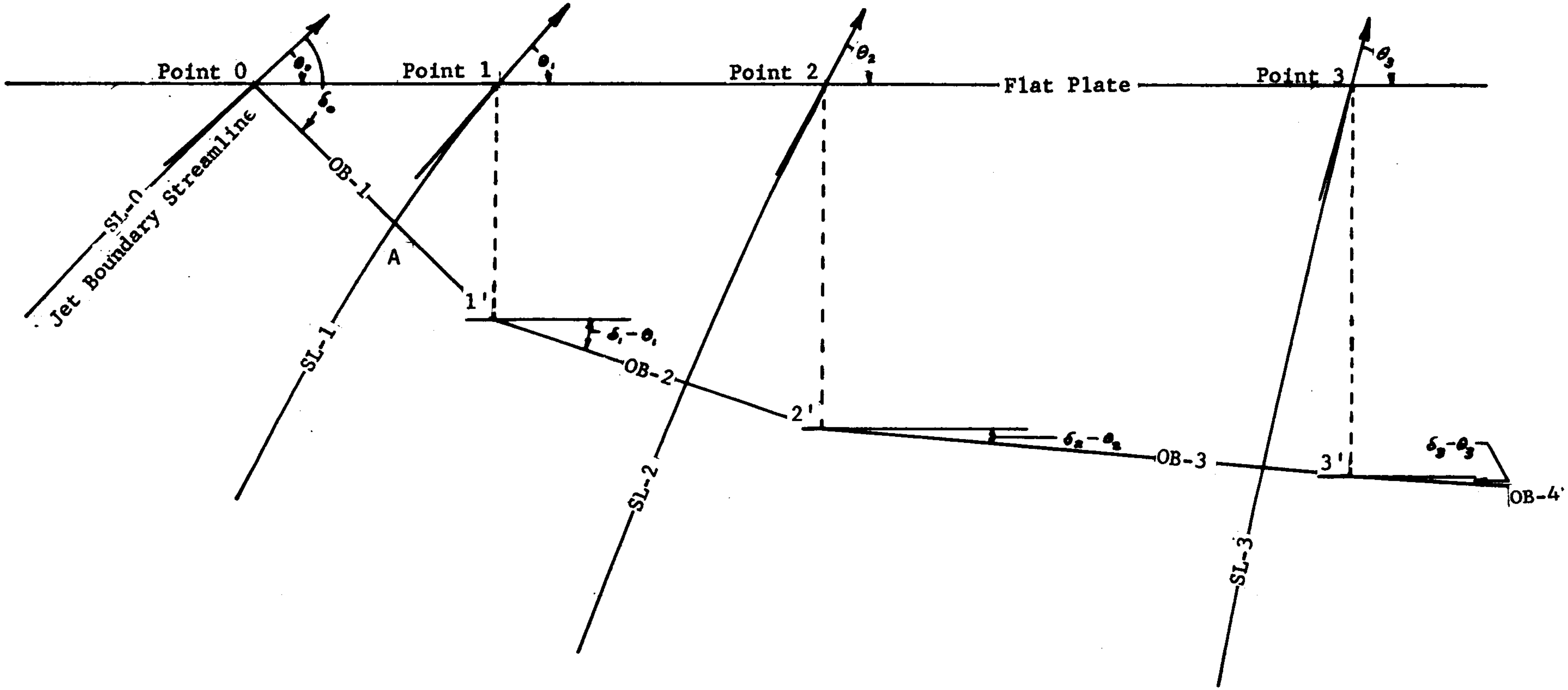


FIGURE 3. MODEL OF SEMI-MINOR AXIS PROFILE OF THE INTERSECTION REGION

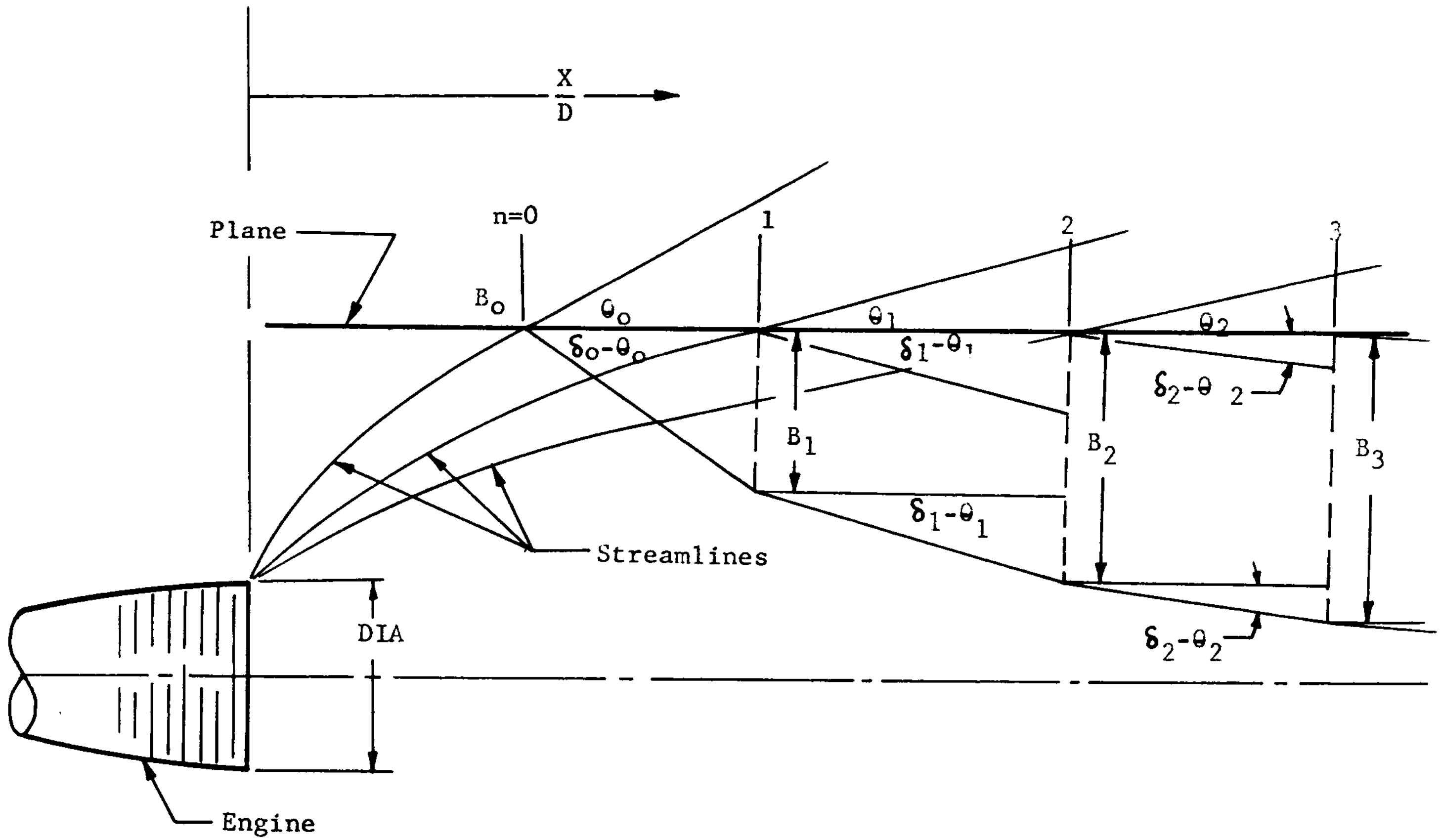


FIGURE 4. GEOMETRY FOR DETERMINING THE SEMI-MINOR AXIS PROFILE OF THE INTERSECTION REGION CROSS SECTION

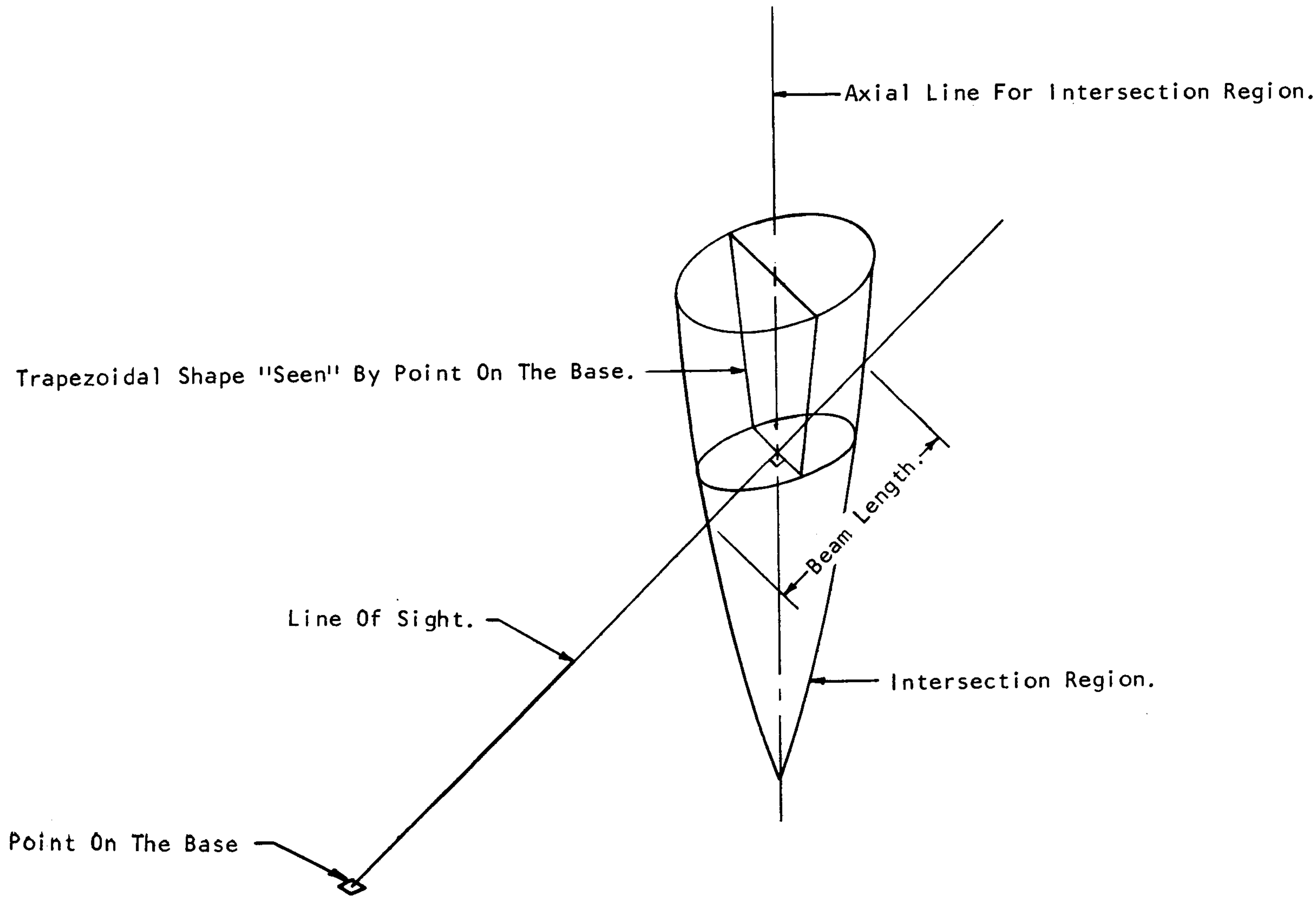


FIGURE 5. SKETCH OF TYPICAL INCREMENT RADIATING TO A POINT ON THE BASE

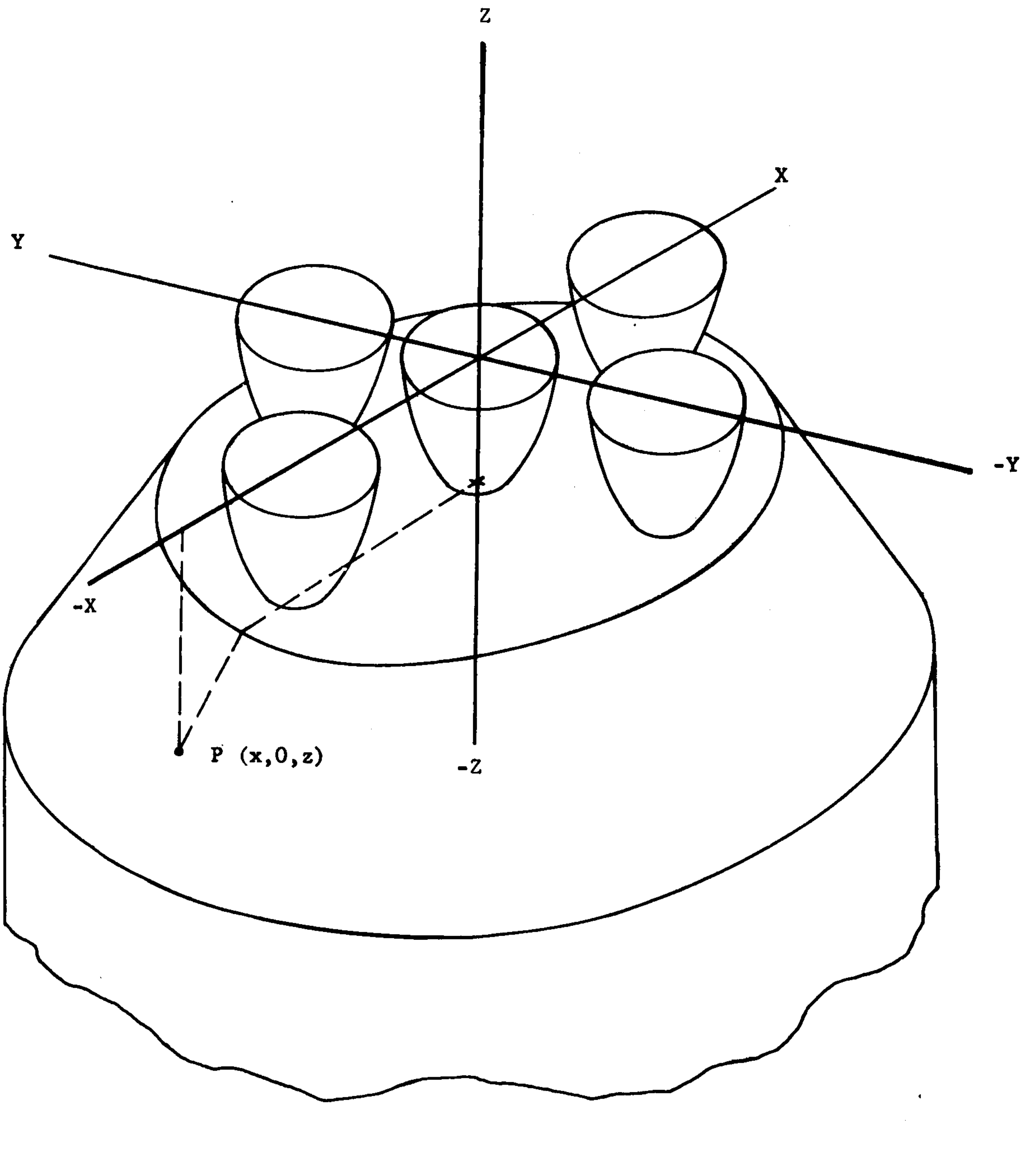


FIGURE 6. RIGHT-HANDED CARTESIAN COORDINATE SYSTEM USED TO LOCATE POINTS ON BASE

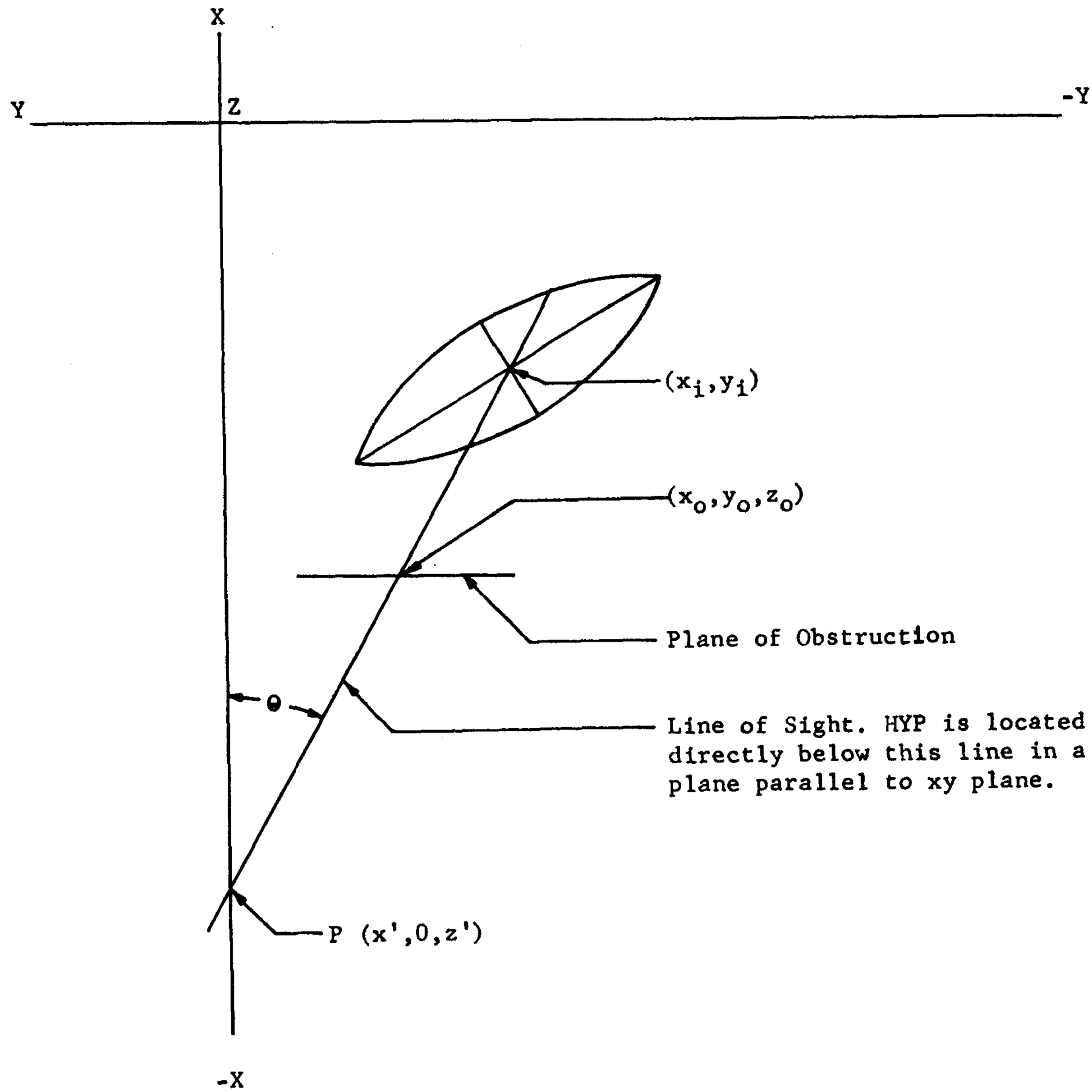


FIGURE 7. PLANE OF OBSTRUCTION GEOMETRY

START CHAIN 1

```
*          SLEM      DASH                 550110   13    FORTRAN    04011
           COMMON   L,GAMMA,    XD(60),FM(60),T(60),RD(60)
           COMMON   P(60),TEMP(60),BDIS(60),ADIS(60)
           DIMENSION    A(60,4),TABL(10),TAB(10),C(60)
     3     RCD,LL,L,MCON,R,PO,TO,GAMMA
           RCD,PBPX
           RCD,((A(I,J),I=1,LL),J=1,4)
           RCD,(XD(J),J=1,L)
           RCD,TABL
           RCD,TAB
           Q=2.
           PRINT 1
     1     FORMAT(1H1,25X17HRADIATION PROGRAM//)
           PRINT 2
     2     FORMAT(27X9HCHAIN (1)///)
           PRINT 1002,PBPX
  1002     FORMAT(23X5HPBPX=,E13.5//)
           DO 204 J=1,L
           ARG=XD(J)
           DO 16 I=1,LL
           DATA=A(I,1)
           IF (DATA-ARG) 16,49,19
    16     CONTINUE
           PRINT 216,ARG
           GO TO 204
    19     IF (DATA-A(1,1)) 20,20,22
    20     PRINT 218,ARG
           GO TO 204
    22     DATAP=A(I-1,1)
           FUNC=(ARG-DATAP)/(DATA-DATAP)
           FMH=A(I,2)
           FML=A(I-1,2)
           IF (FMH-FML) 30,30,27
    27     FMC=FUNC*(FMH-FML)
           FM(J)=FML+FMC
           GO TO 32
    30     FMC=FUNC*(FML-FMH)
           FM(J)=FML-FMC
    32     TH=A(I,3)
           TL=A(I-1,3)
           IF(TH-TL) 38,38,35
    35     TC=FUNC*(TH-TL)
           T(J)=TL+TC
           GO TO 40
    38     TC=FUNC*(TL-TH)
           T(J)=TL-TC
    40     RDH=A(I,4)
           RDL=A(I-1,4)
           IF(RDH-RDL) 46,46,43
    43     RDC=FUNC*(RDH-RDL)
           RD(J)=RDL+RDC
           GO TO 48
    46     RDC=FUNC*(RDL-RDH)
           RD(J)=RDL-RDC
    48     GO TO 52
```

FIGURE 8. RADIATION PROGRAM PRINTOUT

```
   49 FM(J)=A(I,2)                                              053
      T(J)=A(I,3)                                               054
      RD(J)=A(I,4)                                              055
   52 IF(1.6-GAMMA) 61,63,63                                    063
   61 PRINT 220,GAMMA                                           064
      GO TO 71                                                  066
   63 DO 70 K=1,10
      IF(TABL(K)-FM(J)) 70,7001,7001                            068
   70 CONTINUE                                                  071
      PRINT 221                                                 072
      GO TO 72                                                  073
 7001 IF(TAB(K)-T(J)) 71,76,76                                  074
   71 PRINT 222                                                 075
      PRINT 224                                                 076
      IF(J-1) 78,78,72
   78 T(J)=A(1,3)
   72 IF (MCON) 74,74,73                                        077
   73 MCON=0                                                    078
   74 DELTA=1.1344                                              079
      GO TO 145                                                 080
   76 AA=GAMMA+1.                                               081
      AC=FM(J)/Q                                                082
      AAA=GAMMA-1.                                              083
      BB=FM(J)**Q/Q                                             084
      CC=1./(GAMMA*FM(J)**Q)                                    085
      DELI=ASINF(1./FM(J))                                      086
      DLM=CC*(AA*AC**Q-1.+(AA*(1.+AAA*BB+AA*AC**4.))**.5)       087
      DELM=ASINF(DLM**.5)                                       088
      DDEL=DELM-DELI                                            089
      GO TO 100                                                 090
   99 DDEL=T(J)/THETA*DDEL                                      091
  100 DELTA=DELI+DDEL                                           092
      THET=TANF(DELTA)*((AA*BB)/((FM(J)*SINF(DELTA))**Q-1.)-1.) 093
      THETA=ATANF(1./THET)                                      094
      IF(ABSF(THETA-T(J))-.0001) 145,145,120                    095
  120 GO TO 99                                                  096
  145 IF (MCON) 146,157,174                                     097
  146 IF (J-1) 147,147,148                                      098
  147 PRINT 207                                                 099
  148 CP=2.*SINF(T(J))**Q                                       100
      OPP=(CP*(GAMMA/Q)*FM**2.)+1.                              101
      OPC=(GAMMA-1.)/Q                                          102
      OPD=1.+OPC*FM**Q                                          103
      OPE=OPD**(GAMMA/(GAMMA-1.))                               104
      SAV=OPP/OPE                                               105
      P(J)=PO*SAV                                               106
      TEMP(J)=TO*SAV**((GAMMA-1.)/GAMMA)                        107
      PRINT 208,XD(J),FM(J),T(J),P(J),TEMP(J)
      GO TO 190                                                 110
  157 IF (J-1) 158,158,159                                      111
  158 PRINT 210                                                 112
  159 CP=2.*SINF(T(J))**Q                                       113
      OPP=(CP*(GAMMA/Q)*FM**2.)+1.                              114
      OPC=(GAMMA-1.)/Q                                          115
      OPD=1.+OPC*FM**Q                                          116
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
      OPE=OPD**(GAMMA/(GAMMA-1.))
      SAV=OPP/OPE
      P(J)=PO*SAV
      ALPHA=(GAMMA-1.)/(GAMMA+1.)
      BETA=GAMMA*FM**Q *(SINF(T(J)))**Q
      VA=1.+ALPHA
      VB=(GAMMA-1.)*FM**Q/Q
      TEMP(J)=TO*((1.+BETA)*VA+ALPHA*(BETA+BETA**Q))/((1.+VB)*VA+BETA+VB
     9*BETA)
      PRINT 208,XD(J),FM(J),T(J),P(J),TEMP(J)
      GO TO 190
  174 IF (J-1) 175,175,176
  175 PRINT 212
  176 X=(FM**Q)*((SINF(DELTA))**Q)
      Y=Q*GAMMA
      Z=GAMMA-1.
      ZZ=GAMMA+1.
      ZZZ=ZZ**Q
      T2T1=(X*Y-Z)*(Z*X+Q)/(ZZZ*X)
      XX=1.+(Z/Q)*(FM**2.)
      T2TC=T2T1/XX
      TEMP(J)=T2TC*TO
      P2P1=(X*Y-Z)/ZZ
      P2PC=P2P1/(XX**(GAMMA/Z))
      P(J)=PO*P2PC
      PRINT 208,XD(J),FM(J),T(J),P(J),TEMP(J)
  190 C(J)=DELTA-T(J)
      IF (J-1)  192,192,194
  192 BDIS(J)=(TANF(C(J)))*(XD(J)-A(1,1))
      GO TO 195
  194 BDIS(J)=BDIS(J-1)+ TANF(C(J-1))*(XD(J)-XD(J-1))
  195 ADIS(J)=SQRTF(RD(J)**Q-R**Q)
  204 CONTINUE
  205 PRINT 206
  206 FORMAT(1H1)
  207 FORMAT(10X50HISENTROPIC RELATIONS USED FOR TEMP AND P CALCULAT.//)
  208 FORMAT(23X6HXD(J)=,E13.5/,2X8HFM(J)   =,E13.5,2X8HT(J)    =,E13.5,
     92X8HP(J)    =,E13.5,2X8HTEMP(J)=,E13.5///)
  210 FORMAT(10X46HRANKINE-HUGONIOT RELATIONS USED FOR TEMP AND P/
  211 911HCALCULATION///)
  212 FORMAT(10X49HOBLIQUE SHOCK RELATION USED FOR TEMP AND PRESSURE/
  213 911HCALCULATION///)
  216 FORMAT(25HXD VALUE EXCEEDS XD TABLE/
  217 96HXD(J)=,E16.8///)
  218 FORMAT(41HXD VALUE IS LOWER THAN LOWEST IN XD TABLE/
  219 96HXD(J)=,E16.8///)
  220 FORMAT(40HGAMMA EXCEEDS OBLIQUE SHOCK CAPABILITIES/
  220196HGAMMA=,E16.8//)
  221 FORMAT (33HFM(J) EXCEEDS OBLIQUE SHOCK TABLE///)
  222 FORMAT (28HOBLIQUE SHOCK CANNOT BE USED/
  223 926HSWITCH TO RANKINE-HUGONIOT///)
  224 FORMAT(16HDELTA=65 DEGREES///)
  225 CALL CHAIN (2)
  226 END
*     FORTRAN
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
START
CHAIN       COMMON  L,GAMMA,    XD(60),FM(60),T(60),RD(60)
  2         COMMON    P(60),TEMP(60),BDIS(60),ADIS(60)
            COMMON F(60),ANGLE(60),FLE(60),PH20(60),EMISC,DIA,PHI,FXI
            COMMON   FK,SXD,QRAD(60)
            DIMENSION RC(60),TDIS(60),AVTEM(60),EMIS(60),BLED(60),AVP(60)
            DIMENSION XDQ(60),FNRC(60)
            RCD,DIA,FXI,XD(L+1)
            RCD,FK,PHI,SXD
            Q=2.
            VG=SINF(PHI)**Q
            VGG=COSF(PHI)**Q
            DO 2559 J=1,L
            VC=ADIS(J)*BDIS(J)
            VD=ADIS(J)**Q
            VE=BDIS(J)**Q
            RC(J)=VC*(SQRTF(1./(VE*VG+VD*VGG)))
            TDIS(J)=VC*(SQRTF(1./(VE*VGG+VD*VG)))
       2559 CONTINUE
            PRINT 252
            PRINT 426
        252 FORMAT(31X9HCHAIN (2)//)
        262 PRINT 263,FK,PHI
        263 FORMAT(30X3HFK=,E12.5,/30X4HPHI=,E12.5/)
            DO 440 J=1,L
            PRINT 267,J
        267 FORMAT(35X2HJ=,I3/)
            PRINT 269,XD(J)
        269 FORMAT(30X6HXD(J)=,E13.5//)
            IF(ABSF(FK)-RC(J)) 285,271,275
        271 FLE(J)=50.0
            ANGLE(J)=1.570796327
            GO TO 297
        275 UA=ABSF(FK)-RC(J)
            UB=XD(J)+SXD
            ANGLE(J)=ATANF(UB/UA)
            XDQ(J)=XD(J)+TANF(ANGLE(J))*RC(J)
            DO 281 I=J,L
            IF (XD(I)-XDQ(J)) 281,291,291
        281 CONTINUE
            FLE(J)=(RC(J)+RC(L))/(COSF(ANGLE(J)))
            GO TO 294
        285 FLE(J)=25.
            UB=XD(J)+SXD
            UC=RC(J)-ABSF(FK)
            ANGLE(J)=ATANF(UB/UC)
            GO TO 297
        291 FNXD=XD(I)
            FNRC(J)=RC(I)
            FLE(J)=(RC(J)+FNRC(J))/(COSF(ANGLE(J)))
        294 IF (FLE(J)-50.) 297,297,295
        295 FLE(J)=50.
        297 XDI=(SINF(ANGLE(J)))*FLE(J)
            XDS=XD(J)+XDI
            DO 301 I=1,L
            IF (XD(I)-XDS) 301,314,314
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
 301 CONTINUE
     CAREA=(TEMP(L)**4)*(XDS-XD(L))
     N=L-1
     DO 310 KW=J,N
     IF (KW-J) 310,309,310
 309 AREAC=0.
 310 AREAC=AREAC+(TEMP(KW)**4)*(XD(KW+1)-XD(KW))
     TOTA=AREAC+CAREA
     AVTEM(J)=TOTA/(XDS-XD(J))
     AVTEM(J)=AVTEM(J)**.25
     GO TO 321
 314 M=I-1
     DO 318 K=J,M
     IF (K-J) 318,317,318
 317 AREAC=0.
 318 AREAC=AREAC+(TEMP(K)**4)*(XD(K+1)-XD(K))
     TOTA=AREAC
     AVTEM(J)=TOTA/(XD(I)-XD(J))
     AVTEM(J)=AVTEM(J)**.25
 321 IF (XD(L)-XDS) 322,331,331
 322 CPRES=(P(L))*(XDS-XD(L))
     N=L-1
     DO 327 KW=J,N
     IF (KW-J) 327,326,327
 326 AREAP=0.
 327 AREAP=AREAP+(P(KW))*(XD(KW+1)-XD(KW))
     TOTP=AREAP+CPRES
     AVP(J)=TOTP/(XDS-XD(J))
     GO TO 338
 331 MN=I-1
     DO 335 K=J,MN
     IF (K-J) 335,334,335
 334 AREAP=0.
 335 AREAP=AREAP+(P(K))*(XD(K+1)-XD(K))
     TOTP=AREAP
     AVP(J)=TOTP/(XD(I)-XD(J))
 338 BLED(J)=(FLE(J))*DIA
     SIG2=1./SQRTF(FK**Q+(SXD+XD(J))**Q)
     SIG3=1./SQRTF(FK**Q+(SXD+XD(J+1))**Q)
     XXX=SIG2*(-Q*ATANF(TDIS(J)*SIG2))
     YYY=SIG3*(Q*ATANF(TDIS(J)*SIG3))
     F(J)=(FK/6.283185)*(XXX+YYY)
     PH2O(J)=FXI*AVP(J)
     PL=PH2O(J)*BLED(J)
     IF(PL-.001) 3407,3390,3390
3390 IF(PL-.02) 3391,3394,3394
3391 IF(AVTEM(J)-2200.) 3392,3392,3393
3392 A0=.6918E-2-.1035E-4*AVTEM(J)+.5908E-8*AVTEM(J)**2
    9-.1221E-11*AVTEM(J)**3
     A1=4.1462-.3099E-2*AVTEM(J)+.9596E-6*AVTEM(J)**2
    9-.121E-9*AVTEM(J)**3
     A2=-41.808+.2765E-1*AVTEM(J)-.243E-5*AVTEM(J)**2
    9-.1E-8*AVTEM(J)**3
     A3=175.61-.8474E-1*AVTEM(J)-.2372E-4*AVTEM(J)**2
    9+.1303E-7*AVTEM(J)**3
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
      EMIS(J)=A0+A1*PL+A2*PL**2+A3*PL**3
      GO TO 3406
 3393 A0=.1042E-2-.9582E-6*AVTEM(J)+.1574E-9*AVTEM(J)**2
      A1=2.524-.1088E-2*AVTEM(J)+.1197E-6*AVTEM(J)**2
      A2=-28.96+.1552E-1*AVTEM(J)-.1945E-5*AVTEM(J)**2
      EMIS(J)=A0+A1*PL+A2*PL**2
      GO TO 3406
 3394 IF(PL-.1)3395,3395,3400
 3395 IF(AVTEM(J)-2200.) 3396,3396,3397
 3396 GO TO 3392
 3397 IF(AVTEM(J)-3400.) 3398,3399,3399
 3398 A0=.569E-2-.2627E-5*AVTEM(J)-.1168E-9*AVTEM(J)**2
     9+.8381E-13*AVTEM(J)**3
      A1=2.594-.1468E-2*AVTEM(J)+.3207E-6*AVTEM(J)**2
     9-.2583E-10*AVTEM(J)**3
      A2=-.7873-.2297E-2*AVTEM(J)+.9238E-6*AVTEM(J)**2
     9-.7605E-10*AVTEM(J)**3
      A3=-.8534E+2+.8458E-1*AVTEM(J)-.2441E-4*AVTEM(J)**2
     9+.2119E-8*AVTEM(J)**3
      EMIS(J)=A0+A1*PL+A2*PL**2+A3*PL**3
      GO TO 3406
 3399 A0=.1052-.7318E-4*AVTEM(J)+.1645E-7*AVTEM(J)**2
     9-.1208E-11*AVTEM(J)**3
      A1=-2.299+.2014E-2*AVTEM(J)-.4971E-6*AVTEM(J)**2
     9+.3741E-10*AVTEM(J)**3
      A2=66.19-.4732E-1*AVTEM(J)+.1086E-4*AVTEM(J)**2
     9-.7985E-9*AVTEM(J)**3
      A3=-405.9+.2897*AVTEM(J)-.6701E-4*AVTEM(J)**2
     9+.5014E-8*AVTEM(J)**3
      EMIS(J)=A0+A1*PL+A2*PL**2+A3*PL**3
      GO TO 3406
 3400 IF(PL-1.0) 3401,3401,3402
 3401 A0=.1006-.1014E-3*AVTEM(J)+.4390E-7*AVTEM(J)**2
     9-.9089E-11*AVTEM(J)**3+.7098E-15*AVTEM(J)**4
      A1=.7705+.1016E-3*AVTEM(J)-.2288E-6*AVTEM(J)**2
     9+.6294E-10*AVTEM(J)**3-.5309E-14*AVTEM(J)**4
      A2=-1.1784-.3062E-3*AVTEM(J)+.5419E-6*AVTEM(J)**2
     9-.1516E-9*AVTEM(J)**3+.1289E-13*AVTEM(J)**4
      A3=.9306+.5489E-3*AVTEM(J)-.6685E-6*AVTEM(J)**2
     9+.1773E-9*AVTEM(J)**3-.1454E-13*AVTEM(J)**4
      A4=-.2717-.2979E-3*AVTEM(J)+.2938E-6*AVTEM(J)**2
     9-.7382E-10*AVTEM(J)**3+.5799E-14*AVTEM(J)**4
      EMIS(J)=A0+A1*PL+A2*PL**2+A3*PL**3+A4*PL**4
      GO TO 3406
 3402 IF(PL-10.) 3403,3403,3404
 3403 A0=.2814-.6083E-4*AVTEM(J)-.998E-8*AVTEM(J)**2
     9+.2684E-11*AVTEM(J)**3
      A1=+.9226E-1-.3216E-5*AVTEM(J)+.1709E-8*AVTEM(J)**2
     9-.8164E-12*AVTEM(J)**3
      A2=-.1176E-1+.3054E-5*AVTEM(J)-.1514E-8*AVTEM(J)**2
     9+.2766E-12*AVTEM(J)**3
      A3=.5398E-3-.1976E-6*AVTEM(J)+.9794E-10*AVTEM(J)**2
     9-.1646E-13*AVTEM(J)**3
      EMIS(J)=A0+A1*PL+A2*PL**2+A3*PL**3
      GO TO 3406
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
 3404 IF(PL-100.) 3405,3405,3408
 3405 A0=.61295-.1101E-3*AVTEM(J)+.4088E-8*AVTEM(J)**2
      A1=.5569E-2-.8151E-8*AVTEM(J)-.9138E-10*AVTEM(J)**2
      A2=-.2578E-4-.8615E-9*AVTEM(J)+.5913E-12*AVTEM(J)**2
      EMIS(J)=A0+A1*PL+A2*PL**2
      GO TO 3406
 3407 PRINT 430
      GO TO 440
 3408 PRINT 431
      GO TO 440
 3406 SAVE=F(J)*(4.7611E-13)*EMIS(J)*AVTEM(J)**4.
      IF (J-1) 350,348,350
  348 QRADS=0.
      SSF=0.
  350 QRADS=SAVE+QRADS
      SSF=F(J)+SSF
      PRINT 425,BLED(J),AVTEM(J),PH2O(J),SSF,EMIS(J)
      QRAD(J)=SAVE
      PRINT 427,QRAD(J),QRADS
  425 FORMAT(5HBLED=,E13.5,2X6HAVTEM=,E13.5,2X5HPH2O=,E13.5,
     92X4HSSF=,E13.5,2X5HEMIS=,E13.5//)
  427 FORMAT(15X5HQRAD=,E13.5,4X6HQRADS=,E13.5/)
  440 CONTINUE
      PRINT 426
  426 FORMAT(1H ,20X21HQ BY AVT + AVP METHOD//)
      PRINT 4083,QRADS
 4083 FORMAT(27HTOTAL RADIANT HEAT FLUX IS E16.8,2X13HBTU/SEC-SQ FT//)
  414 PRINT 415
  415 FORMAT(1H1)
  430 FORMAT(10X50HPL IS LESS THAN .001 FT-ATM - PROGRAM WILL DISCARD//)
  431 FORMAT(10X49HPL GREATER THAN 100 FT-ATM - PROGRAM WILL DISCARD//)
      CALL CHAIN (3)
START END
CHAIN *
3     FORTRAN
      COMMON  L,GAMMA,   XD(60),FM(60),T(60),RU(60)
      COMMON   P(60),TEMP(60),BDIS(60),ADIS(60)
      COMMON F(60),ANGLE(60),FLE(60),PH2O(60),EMISC,DIA,PHI,FXI
      COMMON  FK,SXD,QRAD(60) ,QRDA(60)
      DIMENSION VAL(51)
      DO 416 J=1,L
      IF(J-1) 350,351,350
  351 PRINT 352
  352 FORMAT(27X9HCHAIN (3)//)
      PRINT 4082
  350 ABSIS=(FLE(J))/50.
      CN=ABSIS*SINF(ANGLE(J))
      DO 3960 I=1,51
      IF (I-1) 361,361,365
  361 CR=XD(J)
      CI=I
      SABSIS=ABSIS*CI*DIA
      GO TO 369
  365 CI=I
      AI=CI-1.
      SABSIS=ABSIS*CI*DIA
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
      CR=CN*AI+XD(J)
 369  DO 392 K=1,L
      IF(CR-XD(K)) 374,371,392
 371  TW=TEMP(K)
      PW=P(K)
      GO TO 395
 374  FUNT=(CR-XD(K-1))/(ABSF(XD(K)-XD(K-1)))
      QTH=TEMP(K)
      QTL=TEMP(K-1)
      IF(QTH-QTL) 381,381,378
 378  TE=FUNT*(QTH-QTL)
      TW=QTL+TE
      GO TO 383
 381  TE=FUNT*(QTL-QTH)
      TW=QTL-TE
 383  QPH=P(K)
      QPL=P(K-1)
      IF(QPH-QPL) 389,389,386
 386  PC=FUNT*(QPH-QPL)
      PW=QPL+PC
      GO TO 395
 389  PC=FUNT*(QPL-QPH)
      PW=QPL-PC
      GO TO 395
 392  CONTINUE
      TW=TEMP(L)
      PW=P(L)
  395 POW=FXI*PW
      POWL=POW*SABSIS
 3950 IF(POWL-.02) 3953,3954,3954
 3953 IF(Tw-2200.) 3956,3956,3957
 3956 A1=4.1462-.3099E-2*Tw+.9596E-6*TW**2-.121E-9*TW**3
      A2=-41.808+.2765E-1*Tw-.243E-5*TW**2-.10E-8*TW**3
      A3=175.61-.8474E-1*Tw-.2372E-4*TW**2+.1303E-7*TW**3
      VAL(I)=A1*POW+2.*A2*(POW**2)*SABSIS+3.*A3*(POW**3)*(SABSIS**2)
      GO TO 3960
 3957 A1=2.524-.1088E-2*Tw+.1197E-6*Tw**2
      A2=-28.96+.1552E-1*Tw-.1945E-5*TW**2
      VAL(I)=A1*POW+2.*A2*(POW**2)*SABSIS
      GO TO 3960
 3954 IF(POWL-.1) 3959,3959,3961
 3959 IF(TW-2200.) 3962,3962,3963
 3962 GO TO 3956
 3963 IF(TW-3400.) 3964,3965,3965
 3964 A1=2.594-.1468E-2*Tw+.3207E-6*TW**2-.2583E-10*Tw**3
      A2=-.7873-.2297E-2*Tw+.9238E-6*TW**2-.7605E-10*TW**3
      A3=-.8534E+2+.8458E-1*Tw-.2441E-4*Tw**2+.2119E-8*Tw**3
      VAL(I)=A1*POW+2.*A2*(POW**2)*SABSIS+3.*A3*(POW**3)*(SABSIS**2)
      GO TO 3960
 3965 A1=-2.299+.2014E-2*TW-.4971E-6*TW**2+.3741E-10*TW**3
      A2=66.19-.4732E-1*Tw+.1086E-4*TW**2-.7985E-9*TW**3
      A3=-405.9+.2897*TW-.6701E-4*TW**2+.5014E-8*Tw**3
      VAL(I)=A1*POW+2.*A2*(POW**2)*SABSIS+3.*A3*(POW**3)*(SABSIS**2)
      GO TO 3960
 3961 IF(POWL-1.0) 3966,3966,3967
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
 3966 A1=.7705+.1016E-3*TW-.2288E-6*TW**2+.6294E-10*TW**3
     9-.5309E-14*TW**4
      A2=-1.1784-.3062E-3*TW+.5419E-6*TW**2-.1516E-9*TW**3
     9+.1289E-13*TW**4
      A3=.9306+.5489E-3*TW-.6885E-6*TW**2+.1775E-9*TW**3
     9-.1454E-13*TW**4
      A4=-.2717-.2979E-3*TW+.2938E-6*TW**2-.7382E-10*TW**3
     9+.5799E-14*TW**4
      VAL(I)=A1*POW+2.*A2*(POW**2)*SABSIS+3.*(POW**3)*(SABSIS**2)
     9+4.*A4*(POW**4)*(SABSIS**3)
      GO TO 3960
 3967 IF(POWL-10.) 3968,3968,3969
 3968 A1=+.9226E-1-.3216E-3*TW+.1709E-8*TW**2-.8164E-12*TW**3
      A2=-.1176E-1+.3054E-5*TW-.1514E-8*TW**2+.2766E-12*TW**3
      A3=.5398E-3-.1976E-6*TW+.9794E-10*TW**2-.1646E-13*TW**3
      VAL(I)=A1*POW+2.*A2*(POW**2)*SABSIS+3.*A3*(POW**3)*(SABSIS**2)
      GO TO 3960
 3969 A1=.5569E-2-.8151E-6*TW-.9138E-10*TW**2
      A2=-.2578E-4-.8615E-9*TW+.5913E-12*TW**2
      VAL(I)=A1*POW+2.*A2*(POW**2)*SABSIS
 3960 VAL(I)=VAL(I)*TW**4
      DO 400 M=2,50,2                                                336
      IF(M-2) 399,399,400                                            337
  399 WE=0.                                                          338
  400 WE=WE+VAL(M)                                                   339
      DO 404 M=1,51,2                                                340
      IF(M-1) 403,403,404                                            341
  403 YOU=0.                                                         342
  404 YOU=YOU+VAL(M)                                                 343
      F=F(J)
      SAVE=ABSIS*4.7611E-13*F*        (-VAL(1)+4.*WE+2.*YOU-VAL(51))/3.  344
      IF(J-1) 408,407,408                                            345
  407 QRDAS=0.                                                       346
  408 QRDAS=SAVE+QRDAS
      PRINT 426,J,XD(J)
  426 FORMAT(30X2HJ=,I3/,22X6HXD(J)=,E13.5//)
      QRDA(J)=SAVE
      PRINT 427, QRDA(J),QRDAS
  427 FORMAT(15X5HQRDA=,E12.5,4X6HQRDAS=,E12.5/)
  416 CONTINUE
      PRINT 4082                                                     348
 4082 FORMAT(20X30HHEAT FLUX BY ABSORPTION METHOD/)                  349
      PRINT 4083, QRDAS
 4083 FORMAT(27HTOTAL RADIANT HEAT FLUX IS E16.8,2X13HBTU/SEC-SQ FT//)
      PRINT 415
  415 FORMAT(1H1)
      CALL CHAIN (4)
  421 CONTINUE
      END
START
CHAIN  *   FORTRAN
4           DIMENSION A(40,4),TDIS(60)
      COMMON L,GAMMA,XD(60),FM(60),T(60),RD(60)
      COMMON   P(60),TEMP(60),BDIS(60),ADIS(60)
      COMMON F(60),ANGLE(60),FLE(60),PH2O(60),EMISC,DIA,PHI,FXI
      COMMON   FK,SXD,QRAD(60)  ,QRDA(60)
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
      RCD,LLLL,FINTX,FINTY
      RCD,((A(I,J),I=1,LLLL),J=1,4)
      RCD,FLAG,PX
      PRINT 252
      PRINT 253
252   FORMAT (27X9HCHAIN (4)//)
253   FORMAT (17X27HBLOCKAGE CORRECTION FACTORS//)
      IF (PX) 32,32,100
100   SI=ASINF(ABSF(FINTY/(FK*DIA)))
      XP=(COSF(SI))*(ABSF(FK))*DIA
      IF(XP-FINTX)30,31,31
31    PX=(XP-FINTX)*(-1.)
      GO TO 32
30    PX=(XP+FINTX)*(-1.)
32    PY=0.
      PZ=(-1.)*SXD*DIA
      DO 69 J=1,L
      Q=2.
      VG=SINF(PHI)**Q
      VGG=COSF(PHI)**Q
      VC=ADIS(J)*BDIS(J)
      VD=ADIS(J)**Q
      VE=BDIS(J)**Q
      TDIS   =VC*(SQRTF(1./(VE*VGG+VD*VG)))
      RC=VC*(SQRTF(1./(VE*VG+VD*VGG)))
      XCOR=TDIS*(SINF(SI))*DIA
      YCOR=TDIS*(COSF(SI))*DIA
      PRINT 999,J
999   FORMAT (24X2HJ=,I3//)
      YR=FINTY-YCOR
      YL=FINTY+YCOR
      IF(FINTY)26,27,27
26    XR=FINTX-XCOR
      XL=FINTX+XCOR
      GO TO 28
27    XR=FINTX+XCOR
      XL=FINTX-XCOR
28    CONTINUE
      DO 49 K=1,3
      IF(K-1)21,21,22
22    IF(K-2)21,23,24
24    IF(K-3)21,25,25
21    PRINT 29
29    FORMAT(19HLEFT SIDE OF REGION//)
998   FLY=0.0
      AINTX=XL-PX
      AINTY=YL
      GO TO 40
23    PRINT 41
41    FORMAT(16HMIDDLE OF REGION//)
      AINTX=FINTX-PX
      AINTY=FINTY
      GO TO 40
25    PRINT 42
42    FORMAT(20HRIGHT SIDE OF REGION//)
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Continued)

```
      AINTX=XR-PX
      AINTY=YR
40    THETA=ATANF(ABSF(AINTY)/(AINTX-PX))
      DO 79 LI=1,LLLL
      ZO=A(LI,3)-PZ
      IF (K-2)  70,71,70
70    FFF=(SQRTF(FK**2.+TDIS**2.))
      HYP=ZO*(FFF/(SXD+XD(J)))
      GO TO 72
71    HYP=ZO*((ABSF(FK)-RC)/(SXD+XD(J)))
72    XO=(COSF(THETA))*HYP
      YO=(SINF(THETA))*HYP
      IF (AINTX) 50,50,51
50    XO=-1.*XO
51    IF  (AINTY)  10,10,11
   10 YO=-1.*YO
   11 H=A(LI,1)
      PRINT 1002,XO,YO
 1002 FORMAT (3HXO=,E16.8,2X3HYO=,E16.8//)
      FFK=A(LI,2)
      RADIUS=A(LI,4)
      EQN=(XO+PX-H)**2.+(YO-FFK)**2.
      SADIUS=RADIUS**2.
      IF (SADIUS-EQN)  79,49,49
  79  CONTINUE
1     FLY=1.+FLY
49    CONTINUE
      QRAD(J)=QRAD(J)*FLY/3.
      QRDA(J)=QRDA(J)*FLY/3.
    5 QRADS=QRADS+QRAD(J)
      QRDAS=QRDAS+QRDA(J)
      PRINT 1005,QRAD(J),QRADS
      PRINT 1006,QRDA(J),QRDAS
1005  FORMAT(5HQRAD=,E16.8,2X6HQRADS=,E16.8//)
1006  FORMAT (5HQRDA=,E16.8,2X6HQRDAS=,E16.8//)
  69  CONTINUE
      PRINT 4038,QRADS,QRDAS
4038  FORMAT (29HWITH BLOCKAGE CORRECTION,THE
     946HRADIATIVE FLUX BY THE AVT. AND AVP. METHOD IS E16.8,2X3HBTU
     910H/SEC-SQ FT/
     932HBY THE ABSORPTION METHOD, IT IS E16.8///)
      PRINT 5000
5000  FORMAT (1H1)
      IF(FLAG) 419,420,419
420   CALL CHAIN (1)
      GO TO 421
419   CALL CHAIN (2)
421   CONTINUE
      END
```

FIGURE 8. RADIATION PROGRAM PRINTOUT (Concluded)

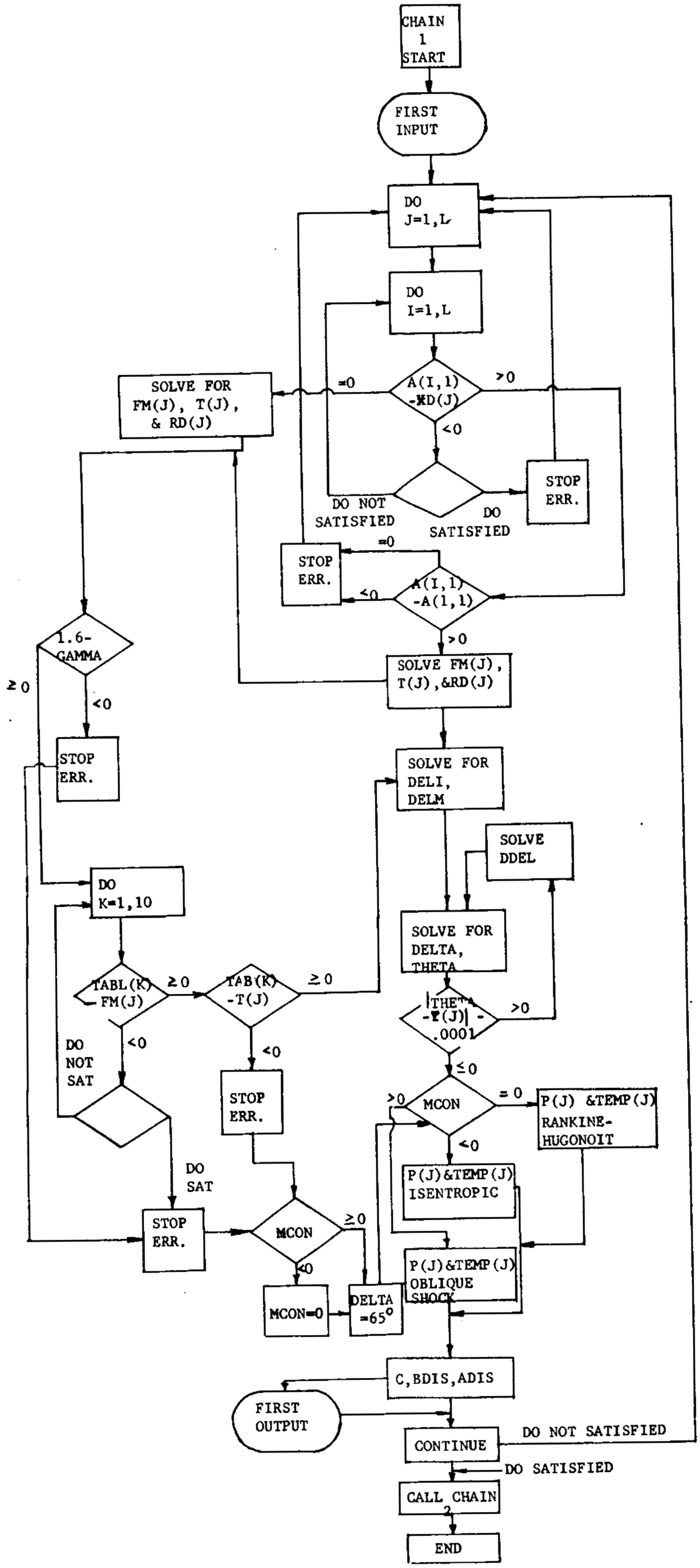


FIGURE 9. FLOW DIAGRAM

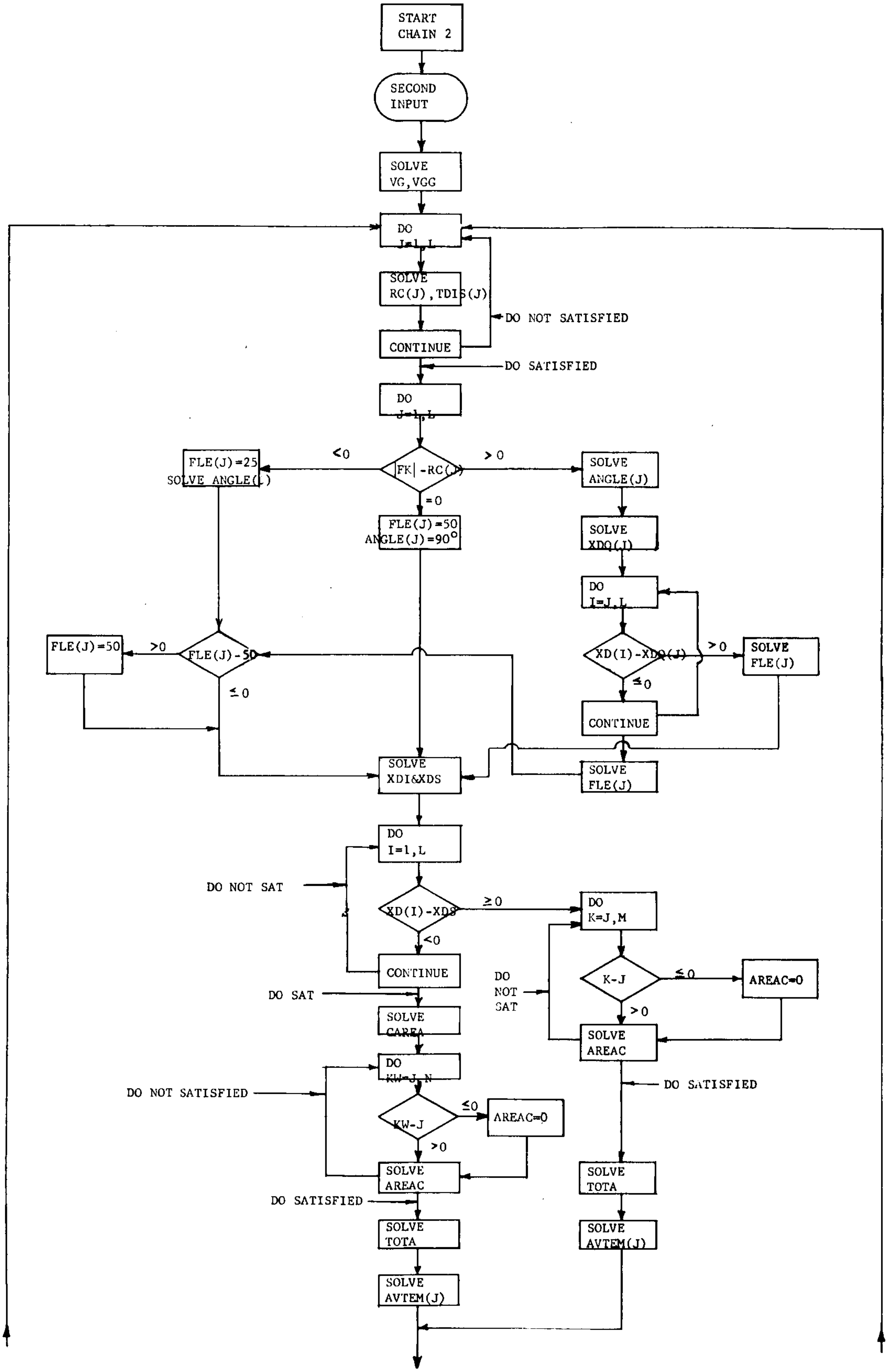


FIGURE 9. FLOW DIAGRAM (Continued)

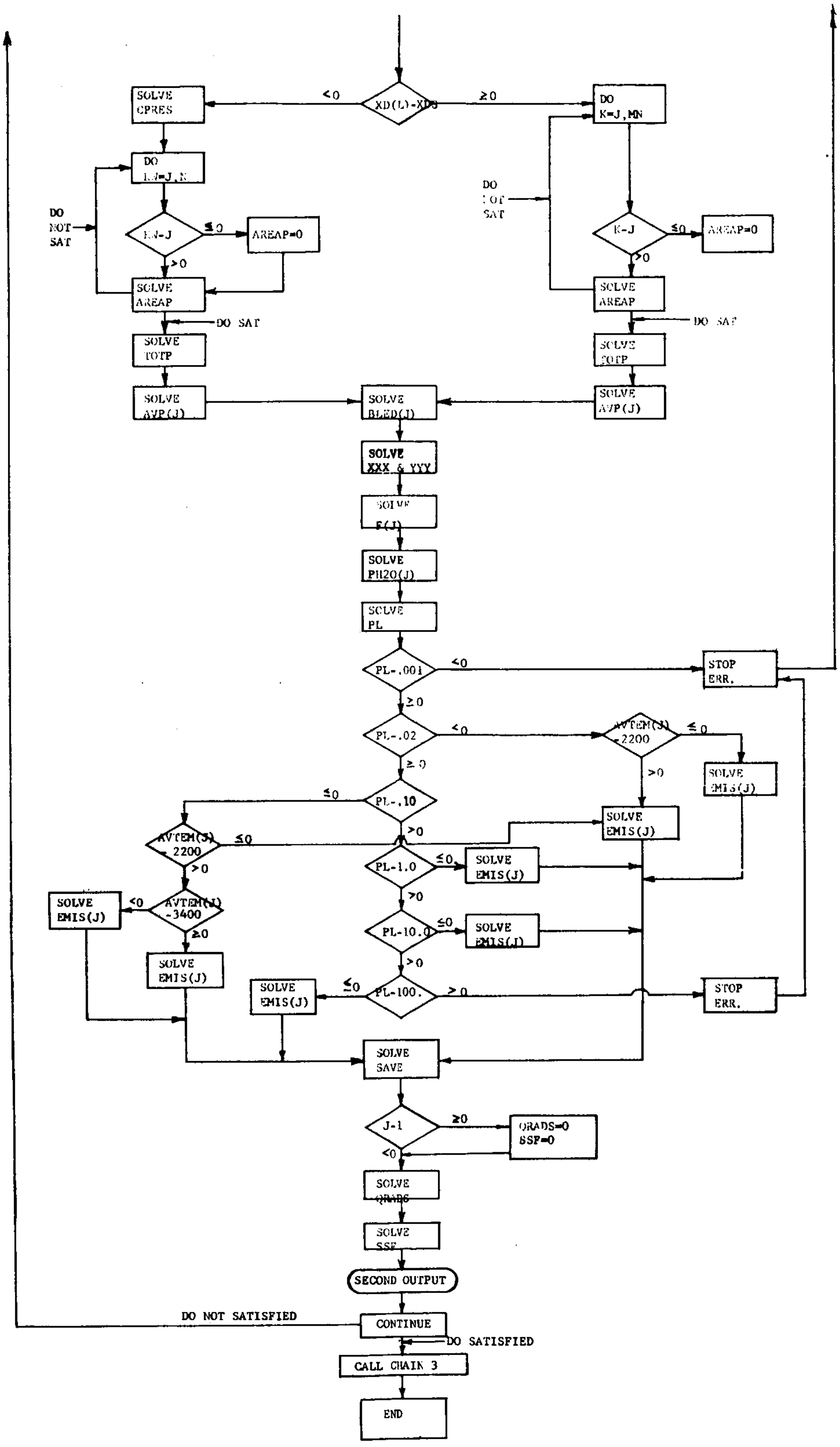


FIGURE 9. FLOW DIAGRAM (Continued)

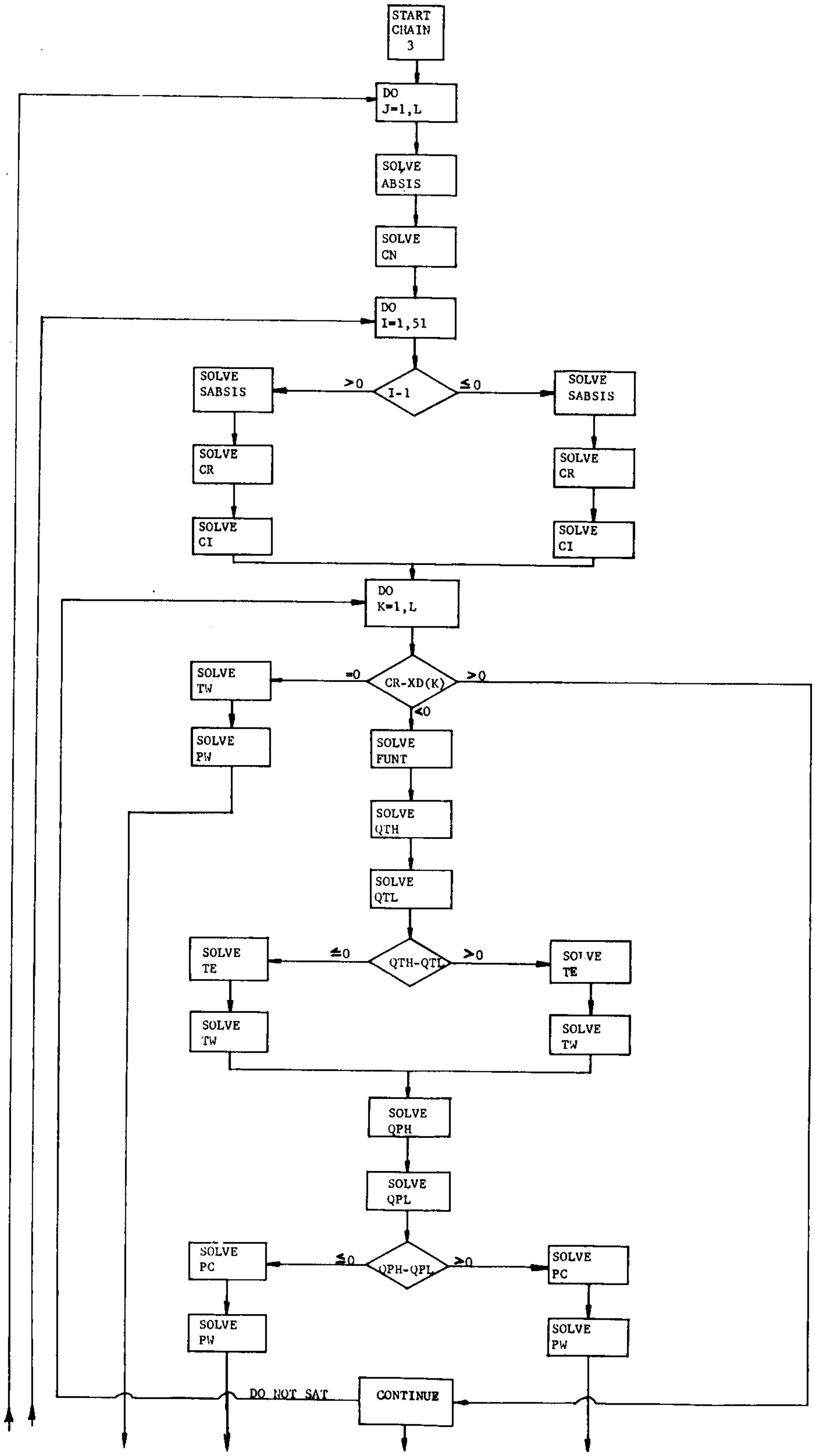


FIGURE 9. FLOW DIAGRAM (Continued)

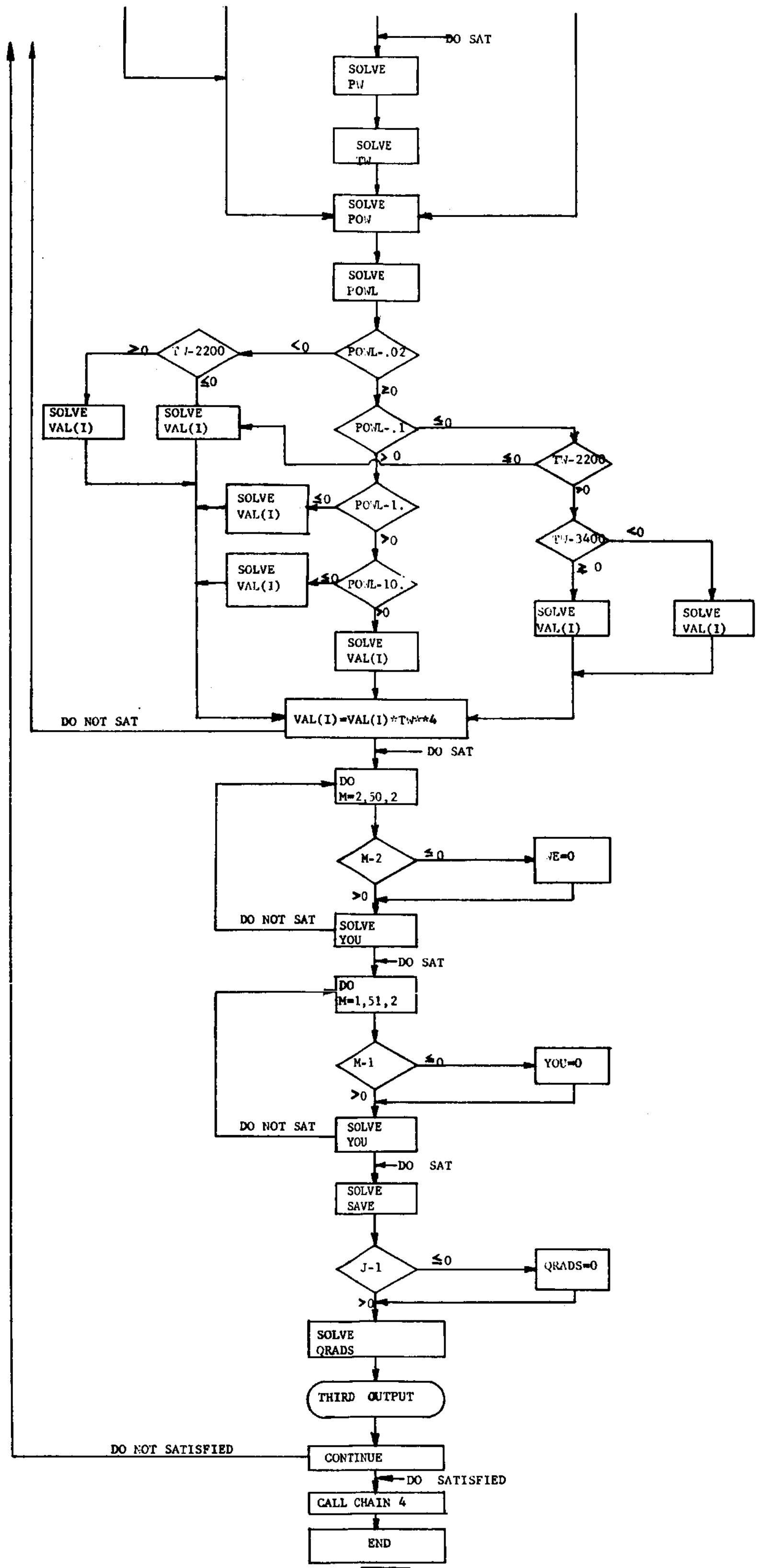


FIGURE 9. FLOW DIAGRAM (Continued)

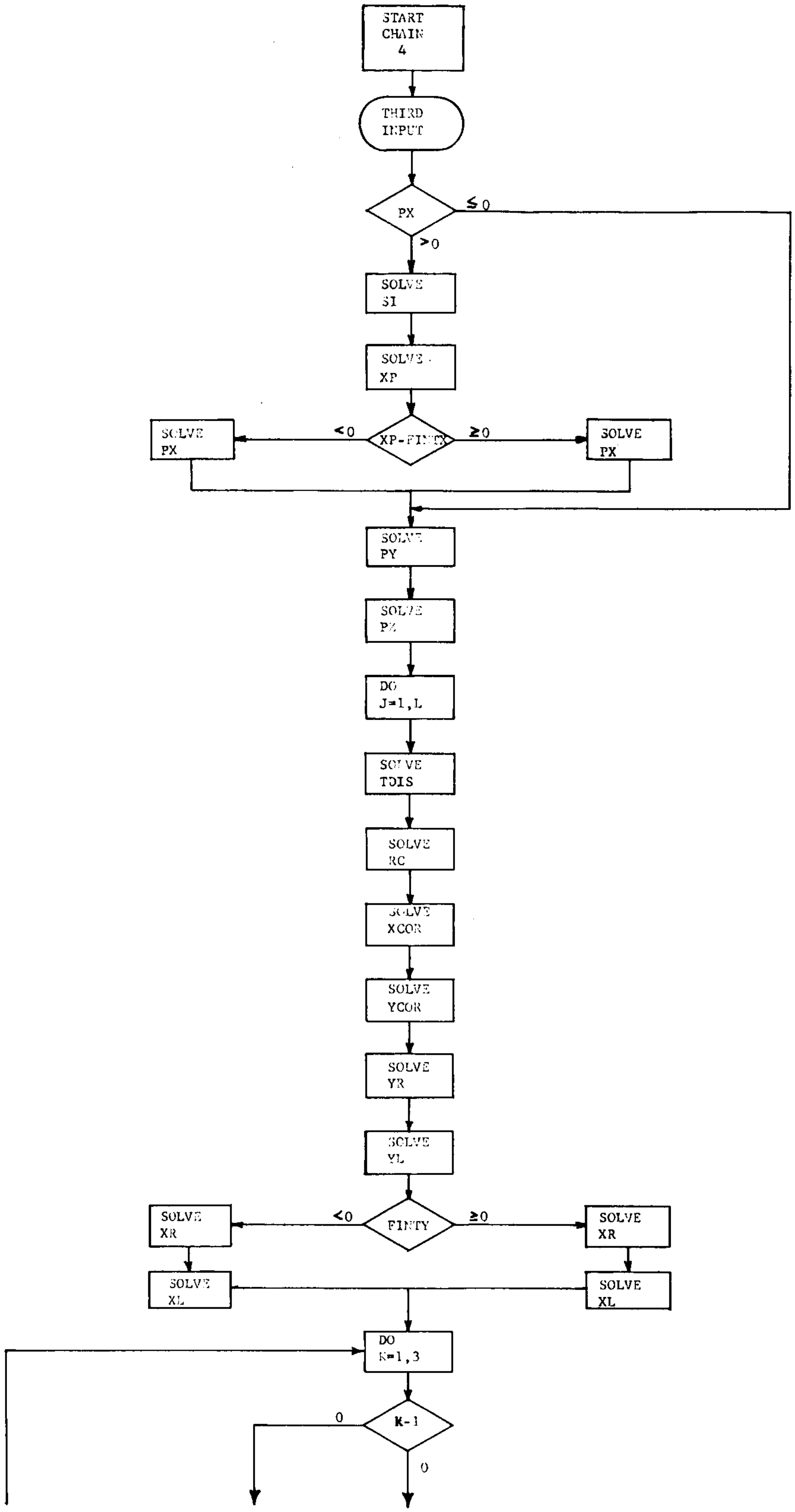


FIGURE 9. FLOW DIAGRAM (Continued)

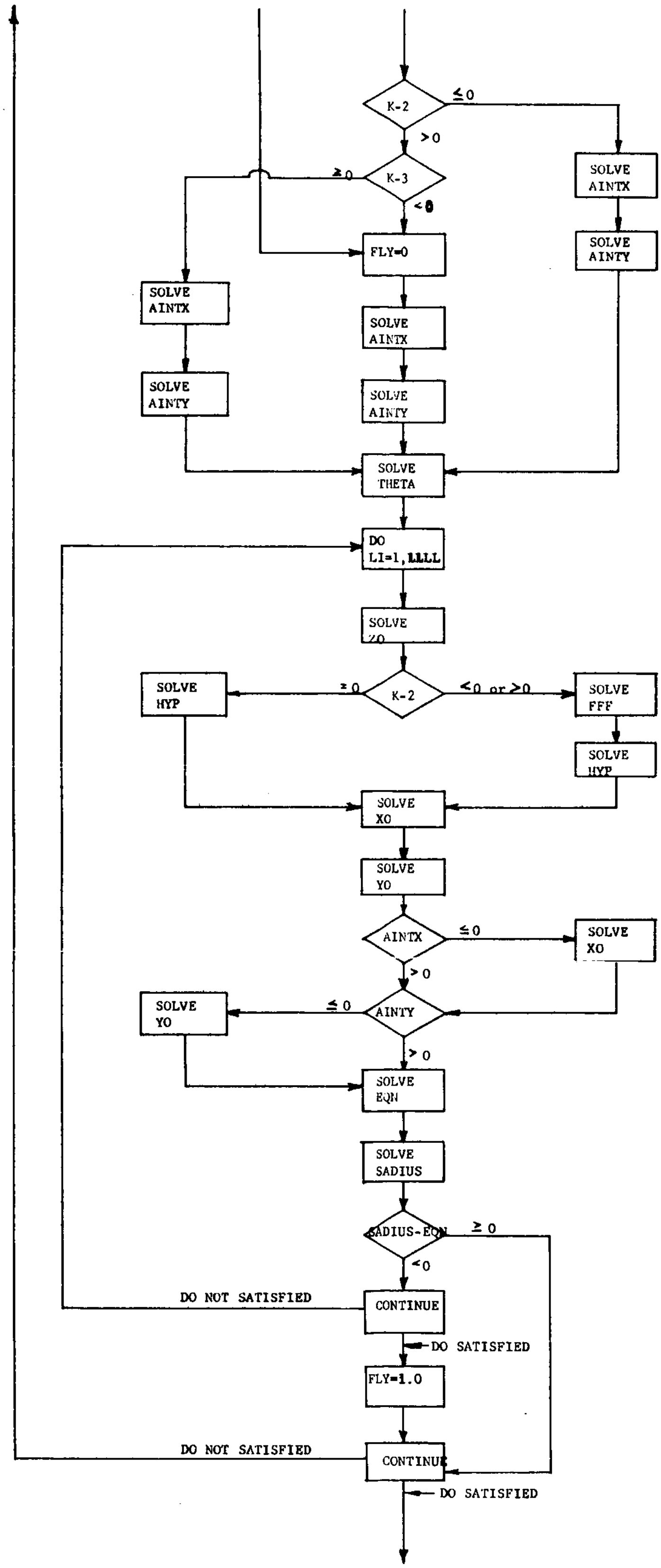


FIGURE 9. FLOW DIAGRAM (Concluded)

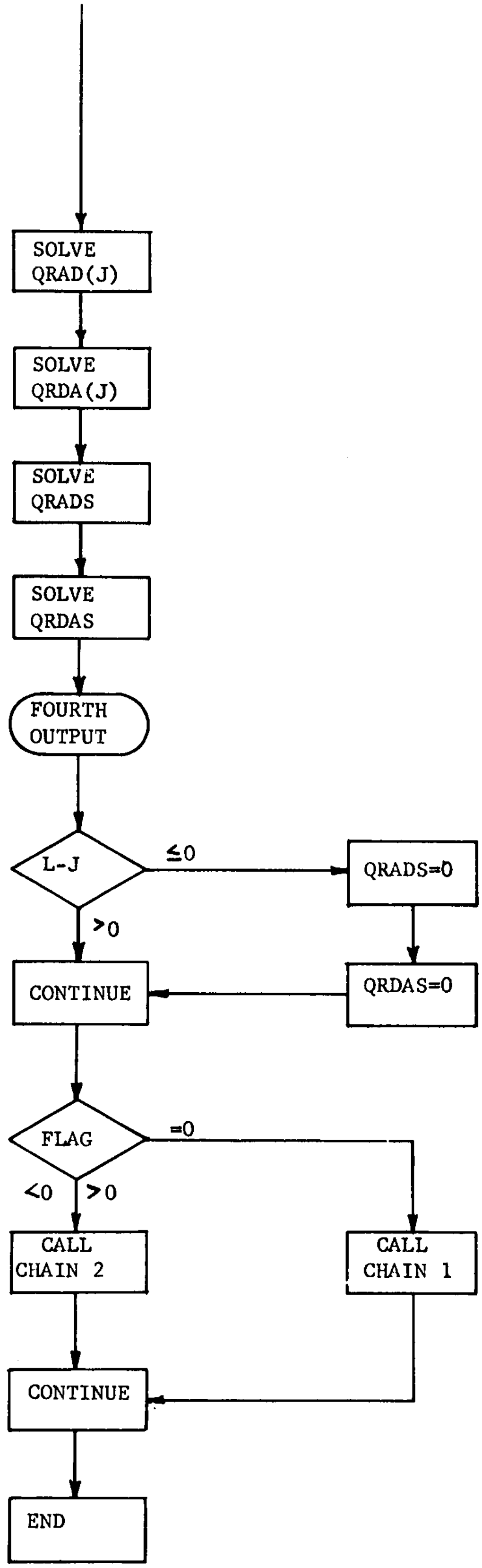


FIGURE 9. FLOW DIAGRAM (Continued)

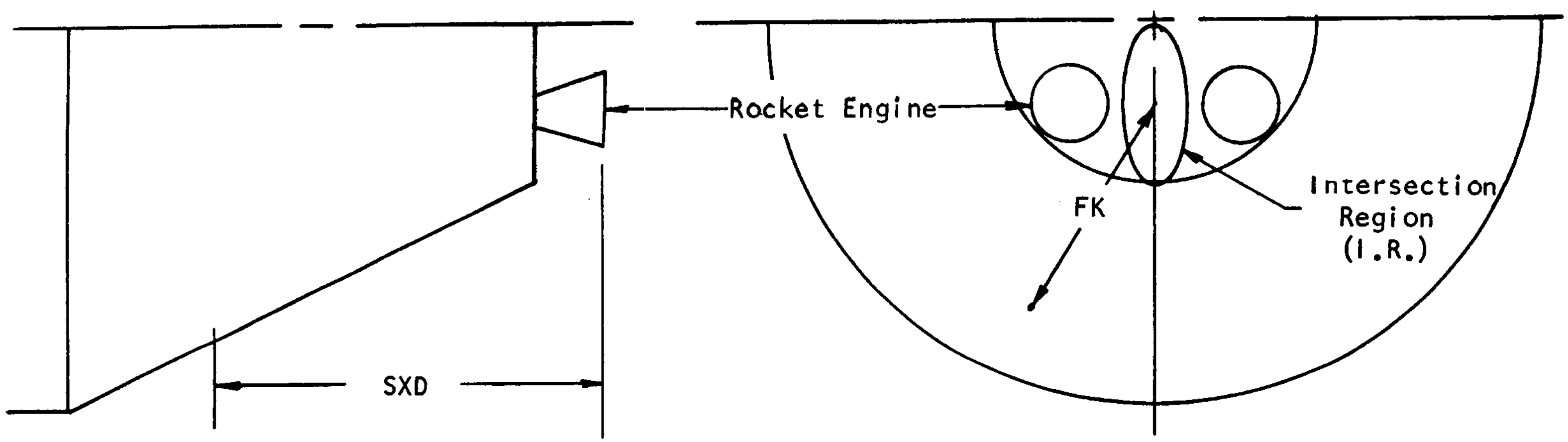


FIGURE 10. BASE GEOMETRY

```
RADIATION PROGRAM

CHAIN (1)

PBPX=  0.18500E-01

OBLIQUE SHOCK RELATION USED FOR TEMP AND PRESSURE
CALCULATION

                    XD(J)=  0.56000E 00
FM(J)  =  0.5567[illegible]E 01  T(J)  =  0.60096E 00  P(J)  =  0.20421E-00  TEMP(J)=  0.33161E 04

                    XD(J)=  0.60000E 00
FM(J)  =  0.5664[illegible]E 01  T(J)  =  0.61031E 00  P(J)  =  0.20820E-00  TEMP(J)=  0.33569E 04

                    XD(J)=  0.70000E 00
FM(J)  =  0.61041E 01  T(J)  =  0.69094E 00  P(J)  =  0.24893E-00  TEMP(J)=  0.37720E 04

                    XD(J)=  0.80000E 00
FM(J)  =  0.60159E 01  T(J)  =  0.64355E 00  P(J)  =  0.22298E-00  TEMP(J)=  0.35075E 04

                    XD(J)=  0.90000E 00
FM(J)  =  0.58791E 01  T(J)  =  0.58998E 00  P(J)  =  0.19527E-00  TEMP(J)=  0.32248E 04

                    XD(J)=  0.10000E 01
FM(J)  =  0.58247E 01  T(J)  =  0.55164E 00  P(J)  =  0.17597E-00  TEMP(J)=  0.30278E 04

                    XD(J)=  0.11000E 01
FM(J)  =  0.57753E 01  T(J)  =  0.51734E 00  P(J)  =  0.15943E-00  TEMP(J)=  0.28587E 04

                    XD(J)=  0.12000E 01
FM(J)  =  0.57269E 01  T(J)  =  0.48813E-00  P(J)  =  0.14597E-00  TEMP(J)=  0.27210E 04

                    XD(J)=  0.13000E 01
FM(J)  =  0.5712[illegible]E 01  T(J)  =  0.46271E-00  P(J)  =  0.13445E-00  TEMP(J)=  0.26030E 04

                    XD(J)=  0.14000E 01
FM(J)  =  0.56966E 01  T(J)  =  0.44055E-00  P(J)  =  0.12481E-00  TEMP(J)=  0.25041E 04

                    XD(J)=  0.15000E 01
FM(J)  =  0.5690[illegible]E 01  T(J)  =  0.42052E-00  P(J)  =  0.11632E-00  TEMP(J)=  0.24168E 04

                    XD(J)=  0.16000E 01
FM(J)  =  0.5690[illegible]E 01  T(J)  =  0.40326E-00  P(J)  =  0.10919E-00  TEMP(J)=  0.23435E 04

                    XD(J)=  0.17000E 01
FM(J)  =  0.56914E 01  T(J)  =  0.38726E-00  P(J)  =  0.10277E-00  TEMP(J)=  0.22773E 04

                    XD(J)=  0.18000E 01
FM(J)  =  0.57004E 01  T(J)  =  0.37324E-00  P(J)  =  0.97241E-01  TEMP(J)=  0.22202E 04

                    XD(J)=  0.19000E 01
FM(J)  =  0.57047E 01  T(J)  =  0.36110E-00  P(J)  =  0.92610E-01  TEMP(J)=  0.21723E 04

                    XD(J)=  0.20000E 01
FM(J)  =  0.5705[illegible]E 01  T(J)  =  0.34974E-00  P(J)  =  0.88419E-01  TEMP(J)=  0.21289E 04

                    XD(J)=  0.21000E 01
FM(J)  =  0.57143E 01  T(J)  =  0.34014E-00  P(J)  =  0.84880E-01  TEMP(J)=  0.20922E 04

                    XD(J)=  0.22000E 01
FM(J)  =  0.5717[illegible]E 01  T(J)  =  0.33151E-00  P(J)  =  0.81806E-01  TEMP(J)=  0.20602E 04

                    XD(J)=  0.23000E 01
FM(J)  =  0.5718[illegible]E 01  T(J)  =  0.32490E-00  P(J)  =  0.79513E-01  TEMP(J)=  0.20364E 04

                    XD(J)=  0.24000E 01
FM(J)  =  0.5707[illegible]E 01  T(J)  =  0.32379E-00  P(J)  =  0.79221E-01  TEMP(J)=  0.20333E 04

                    XD(J)=  0.26000E 01
FM(J)  =  0.57113E 01  T(J)  =  0.32214E-00  P(J)  =  0.78626E-01  TEMP(J)=  0.20271E 04

                    XD(J)=  0.28000E 01
FM(J)  =  0.57195E 01  T(J)  =  0.30942E-00  P(J)  =  0.74282E-01  TEMP(J)=  0.19818E 04

                    XD(J)=  0.30000E 01
FM(J)  =  0.5723[illegible]E 01  T(J)  =  0.30122E-00  P(J)  =  0.71570E-01  TEMP(J)=  0.19534E 04

                    XD(J)=  0.32000E 01
FM(J)  =  0.57173E 01  T(J)  =  0.30013E-00  P(J)  =  0.71266E-01  TEMP(J)=  0.19502E 04

                    XD(J)=  0.33000E 01
FM(J)  =  0.56956E 01  T(J)  =  0.30673E-00  P(J)  =  0.73593E-01  TEMP(J)=  0.19746E 04
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT

```
CHAIN (2)
          Q BY AVT * AVP METHOD
                    FK=-0.81404E 00
                    PHI= 0.15708E 01
                      J= 1
                    XD(J)= 0.56000E 00
BLED= 0.26629E 02  AVTEM= 0.24763E 04  PH2O= 0.66107E-01  SSF= 0.98420E-06  EMIS= 0.22877E-00
          QRAD= 0.40307E-05   QRADS= 0.40307E-05
                      J= 2
                    XD(J)= 0.60000E 00
BLED= 0.57655E 02  AVTEM= 0.22344E 04  PH2O= 0.54985E-01  SSF= 0.16411E-04  EMIS= 0.31177E-00
          QRAD= 0.57074E-04   QRADS= 0.61105E-04
                      J= 3
                    XD(J)= 0.70000E 00
BLED= 0.12166E 03  AVTEM= 0.20916E 04  PH2O= 0.49935E-01  SSF= 0.60190E-04  EMIS= 0.39607E-00
          QRAD= 0.15801E-03   QRADS= 0.21912E-03
                      J= 4
                    XD(J)= 0.80000E 00
BLED= 0.19894E 03  AVTEM= 0.20296E 04  PH2O= 0.48165E-01  SSF= 0.12944E-03  EMIS= 0.44783E-00
          QRAD= 0.25052E-03   QRADS= 0.46964E-03
                      J= 5
                    XD(J)= 0.90000E 00
BLED= 0.33330E 03  AVTEM= 0.19994E 04  PH2O= 0.47248E-01  SSF= 0.21748E-03  EMIS= 0.48461E-00
          QRAD= 0.32466E-03   QRADS= 0.79430E-03
                      J= 6
                    XD(J)= 0.10000E 01
BLED= 0.33330E 03  AVTEM= 0.19935E 04  PH2O= 0.47093E-01  SSF= 0.31932E-03  EMIS= 0.48497E-00
          QRAD= 0.37137E-03   QRADS= 0.11657E-02
                      J= 7
                    XD(J)= 0.11000E 01
BLED= 0.16665E 03  AVTEM= 0.20035E 04  PH2O= 0.47566E-01  SSF= 0.43137E-03  EMIS= 0.42864E-00
          QRAD= 0.36843E-03   QRADS= 0.15341E-02
                      J= 8
                    XD(J)= 0.12000E 01
BLED= 0.16665E 03  AVTEM= 0.19970E 04  PH2O= 0.47350E-01  SSF= 0.55094E-03  EMIS= 0.42885E-00
          QRAD= 0.38834E-03   QRADS= 0.19224E-02
                      J= 9
                    XD(J)= 0.13000E 01
BLED= 0.16665E 03  AVTEM= 0.19921E 04  PH2O= 0.47168E-01  SSF= 0.67602E-03  EMIS= 0.42899E-00
          QRAD= 0.40229E-03   QRADS= 0.23247E-02
                      J= 10
                    XD(J)= 0.14000E 01
BLED= 0.16665E 03  AVTEM= 0.19882E 04  PH2O= 0.47015E-01  SSF= 0.80496E-03  EMIS= 0.42907E-00
          QRAD= 0.41156E-03   QRADS= 0.27363E-02
                      J= 11
                    XD(J)= 0.15000E 01
BLED= 0.16665E 03  AVTEM= 0.19851E 04  PH2O= 0.46886E-01  SSF= 0.93649E-03  EMIS= 0.42912E-00
          QRAD= 0.41729E-03   QRADS= 0.31536E-02
                      J= 12
                    XD(J)= 0.16000E 01
BLED= 0.16665E 03  AVTEM= 0.19827E 04  PH2O= 0.46779E-01  SSF= 0.10696E-02  EMIS= 0.42914E-00
          QRAD= 0.42025E-03   QRADS= 0.35738E-02
                      J= 13
                    XD(J)= 0.17000E 01
BLED= 0.16665E 03  AVTEM= 0.19808E 04  PH2O= 0.46689E-01  SSF= 0.12035E-02  EMIS= 0.42915E-00
          QRAD= 0.42102E-03   QRADS= 0.39949E-02
                      J= 14
                    XD(J)= 0.18000E 01
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
BLED=  0.16665E 03  AVTEM=  0.19793E 04  PH20=  0.46615E-01  SSF=  0.13374E-02  EMIS=  0.42916E-00

              QRAD=  0.42008E-03    QRADS=  0.44149E-02
                              J= 15
                          XD(J)=  0.19000E 01

BLED=  0.16665E 03  AVTEM=  0.19781E 04  PH20=  0.46556E-01  SSF=  0.14710E-02  EMIS=  0.42915E-00

              QRAD=  0.41776E-03    QRADS=  0.48327E-02
                              J= 16
                          XD(J)=  0.20000E 01

BLED=  0.16665E 03  AVTEM=  0.19772E 04  PH20=  0.46507E-01  SSF=  0.16037E-02  EMIS=  0.42915E-00

              QRAD=  0.41438E-03    QRADS=  0.52471E-02
                              J= 17
                          XD(J)=  0.21000E 01

BLED=  0.16665E 03  AVTEM=  0.19765E 04  PH20=  0.46470E-01  SSF=  0.17353E-02  EMIS=  0.42914E-00

              QRAD=  0.41020E-03    QRADS=  0.56573E-02
                              J= 18
                          XD(J)=  0.22000E 01

BLED=  0.16665E 03  AVTEM=  0.19759E 04  PH20=  0.46441E-01  SSF=  0.18654E-02  EMIS=  0.42914E-00

              QRAD=  0.40534E-03    QRADS=  0.60626E-02
                              J= 19
                          XD(J)=  0.23000E 01

BLED=  0.16665E 03  AVTEM=  0.19756E 04  PH20=  0.46420E-01  SSF=  0.19939E-02  EMIS=  0.42913E-00

              QRAD=  0.39998E-03    QRADS=  0.64626E-02
                              J= 20
                          XD(J)=  0.24000E 01

BLED=  0.16665E 03  AVTEM=  0.19753E 04  PH20=  0.46405E-01  SSF=  0.22397E-02  EMIS=  0.42913E-00

              QRAD=  0.76458E-03    QRADS=  0.72272E-02
                              J= 21
                          XD(J)=  0.26000E 01

BLED=  0.16665E 03  AVTEM=  0.19748E 04  PH20=  0.46376E-01  SSF=  0.24783E-02  EMIS=  0.42912E-00

              QRAD=  0.74149E-03    QRADS=  0.79687E-02
                              J= 22
                          XD(J)=  0.28000E 01

BLED=  0.16665E 03  AVTEM=  0.19744E 04  PH20=  0.46350E-01  SSF=  0.27092E-02  EMIS=  0.42911E-00

              QRAD=  0.71673E-03    QRADS=  0.86854E-02
                              J= 23
                          XD(J)=  0.30000E 01

BLED=  0.16665E 03  AVTEM=  0.19743E 04  PH20=  0.46347E-01  SSF=  0.29320E-02  EMIS=  0.42911E-00

              QRAD=  0.69159E-03    QRADS=  0.93770E-02
                              J= 24
                          XD(J)=  0.32000E 01

BLED=  0.16665E 03  AVTEM=  0.19745E 04  PH20=  0.46357E-01  SSF=  0.30422E-02  EMIS=  0.42911E-00

              QRAD=  0.34223E-03    QRADS=  0.97192E-02
                              J= 25
                          XD(J)=  0.33000E 01

BLED=  0.16665E 03  AVTEM=  0.19776E 04  PH20=  0.46648E-01  SSF=  0.32027E-02  EMIS=  0.42938E-00

              QRAD=  0.50173E-03    QRADS=  0.10221E-01
                    Q BY AVT + AVP METHOD

TOTAL RADIANT HEAT FLUX IS   0.10220942E-01   BTU/SEC-SQ FT
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
CHAIN (3)

HEAT FLUX BY ABSORPTION METHOD
                J=  1
      XD(J)=  0.56000E 00

QRDA= 0.29731E-05    QRDAS= 0.29731E-05
                J=  2
      XD(J)=  0.60000E 00

QRDA= 0.51711E-04    QRDAS= 0.54685E-04
                J=  3
      XD(J)=  0.70000E 00

QRDA= 0.15404E-03    QRDAS= 0.20872E-03
                J=  4
      XD(J)=  0.80000E 00

QRDA= 0.27099E-03    QRDAS= 0.47972E-03
                J=  5
      XD(J)=  0.90000E 00

QRDA= 0.47332E-03    QRDAS= 0.95304E-03
                J=  6
      XD(J)=  0.10000E 01

QRDA= 0.34710E-03    QRDAS= 0.13001E-02
                J=  7
      XD(J)=  0.11000E 01

QRDA= 0.16509E-03    QRDAS= 0.14652E-02
                J=  8
      XD(J)=  0.12000E 01

QRDA= 0.15263E-03    QRDAS= 0.16179E-02
                J=  9
      XD(J)=  0.13000E 01

QRDA= 0.14497E-03    QRDAS= 0.17628E-02
                J= 10
      XD(J)=  0.14000E 01

QRDA= 0.13931E-03    QRDAS= 0.19021E-02
                J= 11
      XD(J)=  0.15000E 01

QRDA= 0.13430E-03    QRDAS= 0.20364E-02
                J= 12
      XD(J)=  0.16000E 01

QRDA= 0.13116E-03    QRDAS= 0.21676E-02
                J= 13
      XD(J)=  0.17000E 01

QRDA= 0.12753E-03    QRDAS= 0.22951E-02
                J= 14
      XD(J)=  0.18000E 01

QRDA= 0.12678E-03    QRDAS= 0.24219E-02
                J= 15
      XD(J)=  0.19000E 01

QRDA= 0.12536E-03    QRDAS= 0.25472E-02
                J= 16
      XD(J)=  0.20000E 01

QRDA= 0.12344E-03    QRDAS= 0.26707E-02
                J= 17
      XD(J)=  0.21000E 01

QRDA= 0.12173E-03    QRDAS= 0.27924E-02
                J= 18
      XD(J)=  0.22000E 01

QRDA= 0.11904E-03    QRDAS= 0.29115E-02
                J= 19
      XD(J)=  0.23000E 01

QRDA= 0.11703E-03    QRDAS= 0.30285E-02
                J= 20
      XD(J)=  0.24000E 01

QRDA= 0.22288E-03    QRDAS= 0.32514E-02
                J= 21
      XD(J)=  0.26000E 01

QRDA= 0.21511E-03    QRDAS= 0.34665E-02
                J= 22
      XD(J)=  0.28000E 01

QRDA= 0.20886E-03    QRDAS= 0.36753E-02
                J= 23
      XD(J)=  0.30000E 01

QRDA= 0.20136E-03    QRDAS= 0.38767E-02
                J= 24
      XD(J)=  0.32000E 01

QRDA= 0.99589E-04    QRDAS= 0.39763E-02
                J= 25
      XD(J)=  0.33000E 01

QRDA= 0.14521E-03    QRDAS= 0.41215E-02
       HEAT FLUX BY ABSORPTION METHOD
TOTAL RADIANT HEAT FLUX IS   0.41214981E-02  BTU/SEC-SQ FT
```

```
CHAIN (4)

BLOCKAGE CORRECTION FACTORS

                J=  1

LEFT SIDE OF REGION

XO=  0.32398679E 01  YO=  0.13755223E-02

MIDDLE OF REGION

XO=  0.27116959E 01  YO= -0.13271311E-05

RIGHT SIDE OF REGION

XO=  0.32398679E 01  YO= -0.13755223E-02

QRAD=  0.                QRADS=  0.

QRDA=  0.                QRDAS=  0.

                J=  2

LEFT SIDE OF REGION

XO=  0.31019037E 01  YO=  0.90989337E-02

MIDDLE OF REGION

XO=  0.21259402E 01  YO= -0.10404564E-05

RIGHT SIDE OF REGION

XO=  0.31019037E 01  YO= -0.90989337E-02

QRAD=  0.                QRADS=  0.

QRDA=  0.                QRDAS=  0.

                J=  3

LEFT SIDE OF REGION

XO=  0.30786983E 01  YO=  0.27421087E-01

MIDDLE OF REGION

XO=  0.13030413E 01  YO= -0.68176835E-06

RIGHT SIDE OF REGION

XO=  0.30786983E 01  YO= -0.27421087E-01

QRAD=  0.                QRADS=  0.

QRDA=  0.                QRDAS=  0.

                J=  4

LEFT SIDE OF REGION

XO=  0.29744792E 01  YO=  0.46014039E-01

MIDDLE OF REGION

XO=  0.89169564E 00  YO= -0.43640478E-06

XO=  0.11785444E 01  YO= -0.57679154E-06

XO=  0.11785444E 01  YO= -0.57679154E-06

XO=  0.11785444E 01  YO= -0.57679154E-06

XO=  0.11785444E 01  YO= -0.57679154E-06

XO=  0.11785444E 01  YO= -0.57679154E-06

RIGHT SIDE OF REGION

XO=  0.29744792E 01  YO= -0.46014039E-01

QRAD=  0.83507113E-04  QRADS=  0.83507113E-04

QRDA=  0.90331561E-04  QRDAS=  0.90331561E-04

                J=  5

LEFT SIDE OF REGION

XO=  0.28780407E 01  YO=  0.62010382E-01

MIDDLE OF REGION

XO=  0.48406982E-0   YO= -0.23788743E-06

XO=  0.64243330E 00  YO= -0.31441329E-06

XO=  0.64243330E 00  YO= -0.31441329E-06

XO=  0.64243330E 00  YO= -0.31441329E-06

XO=  0.64243330E 00  YO= -0.31441329E-06

XO=  0.64243330E 00  YO= -0.31441329E-06

RIGHT SIDE OF REGION

XO=  0.28780407E 01  YO= -0.62010382E-01

QRAD=  0.10821874E-03  QRADS=  0.19172585E-03

QRDA=  0.15777324E-03  QRDAS=  0.24810482E-03
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
LEFT SIDE OF REGION
XO=  0.27884704E 01  YO=  0.75930348E-01
MIDDLE OF REGION
XO=  0.15402518E-0   YO= -0.75381465E-07
XO=  0.20357344E-0   YO= -0.99630880E-07
XO=  0.20357344E-0   YO= -0.99630880E-07
XO=  0.20357344E-0   YO= -0.99630880E-07
XO=  0.20357344E-0   YO= -0.99630880E-07
XO=  0.20357344E-0   YO= -0.99630880E-07
RIGHT SIDE OF REGION
XO=  0.27884704E 01  YO= -0.75930348E-01
QRAD=  0.12379024E-03  QRADS=  0.31551611E-03
QRDA=  0.11569977E-03  QRDAS=  0.36380459E-03

                    J=  7
LEFT SIDE OF REGION
XO=  0.27050731E 01  YO=  0.88363512E-01
MIDDLE OF REGION
XO= -0.15217634E-0   YO=  0.74476623E-07
XO= -0.20112984E-0   YO=  0.98434959E-07
XO= -0.20112984E-0   YO=  0.98434959E-07
XO= -0.20112984E-0   YO=  0.98434959E-07
XO= -0.20112984E-0   YO=  0.98434959E-07
XO= -0.20112984E-0   YO=  0.98434959E-07
RIGHT SIDE OF REGION
XO=  0.27050731E 01  YO= -0.88363512E-01
QRAD=  0.12280923E-03  QRADS=  0.43832534E-03
QRDA=  0.55029324E-04  QRDAS=  0.41883391E-03

                    J=  8
LEFT SIDE OF REGION
XO=  0.26272500E 01  YO=  0.99630207E-01
MIDDLE OF REGION
XO= -0.39427631E 00  YO=  0.19296277E-06
XO= -0.52111080E 00  YO=  0.25503684E-06
XO= -0.52111080E 00  YO=  0.25503684E-06
XO= -0.52111080E 00  YO=  0.25503684E-06
XO= -0.52111080E 00  YO=  0.25503684E-06
XO= -0.52111080E 00  YO=  0.25503684E-06
RIGHT SIDE OF REGION
XO=  0.26272500E 01  YO= -0.99630207E-01
QRAD=  0.12944676E-03  QRADS=  0.56777211E-03
QRDA=  0.50876244E-04  QRDAS=  0.46971016E-03

                    J=  9
LEFT SIDE OF REGION
XO=  0.25545007E 01  YO=  0.10999485E-00
MIDDLE OF REGION
XO= -0.60314469E 00  YO=  0.29518505E-06
XO= -0.79716991E 00  YO=  0.39014294E-06
XO= -0.79716991E 00  YO=  0.39014294E-06
XO= -0.79716991E 00  YO=  0.39014294E-06
XO= -0.79716991E 00  YO=  0.39014294E-06
XO= -0.79716991E 00  YO=  0.39014294E-06
RIGHT SIDE OF REGION
XO=  0.25545007E 01  YO= -0.10999485E-00
QRAD=  0.13409615E-03  QRADS=  0.70186826E-03
QRDA=  0.48322777E-04  QRDAS=  0.51803293E-03

                    J= 10
LEFT SIDE OF REGION
XO=  0.24863580E 01  YO=  0.11956636E-00
MIDDLE OF REGION
XO= -0.79278693E 00  YO=  0.38799786E-06
XO= -0.10478180E 01  YO=  0.51281264E-06
XO= -0.10478180E 01  YO=  0.51281264E-06
XO= -0.10478180E 01  YO=  0.51281264E-06
XO= -0.10478180E 01  YO=  0.51281264E-06
XO= -0.10478180E 01  YO=  0.51281264E-06
RIGHT SIDE OF REGION
XO=  0.24863580E 01  YO= -0.11956636E 00
QRAD=  0.13718614E-03  QRADS=  0.83905440E-03
QRDA=  0.46436353E-04  QRDAS=  0.56446920E-03

                    J= 11
LEFT SIDE OF REGION
XO=  0.24224355E 01  YO=  0.12849395E-00
MIDDLE OF REGION
XO= -0.96831822E 00  YO=  0.47390463E-06
XO= -0.12798159E 01  YO=  0.62635470E-06
XO= -0.12798159E 01  YO=  0.62635470E-06
XO= -0.12798159E 01  YO=  0.62635470E-06
XO= -0.12798159E 01  YO=  0.62635470E-06
XO= -0.12798159E 01  YO=  0.62635470E-06
RIGHT SIDE OF REGION
XO=  0.24224355E 01  YO= -0.12849395E-00
QRAD=  0.13909787E-03  QRADS=  0.97815227E-03
QRDA=  0.44766031E-04  QRDAS=  0.60923532E-03

                    J= 12
LEFT SIDE OF REGION
XO=  0.23623776E 01  YO=  0.13686175E-00
MIDDLE OF REGION
XO= -0.11193457E 01  YO=  0.54781897E-06
XO= -0.14794272E 01  YO=  0.72404650E-06
XO= -0.14794272E 01  YO=  0.72404650E-06
XO= -0.14794272E 01  YO=  0.72404650E-06
XO= -0.14794272E 01  YO=  0.72404650E-06
XO= -0.14794272E 01  YO=  0.72404650E-06
RIGHT SIDE OF REGION
XO=  0.23623776E 01  YO= -0.13686175E-00
QRAD=  0.14008454E-03  QRADS=  0.11182368E-02
QRDA=  0.43719080E-04  QRDAS=  0.65295439E-03

                    J= 13
LEFT SIDE OF REGION
XO=  0.23058719E 01  YO=  0.14474706E-00
MIDDLE OF REGION
XO= -0.12529729E 01  YO=  0.61321748E-06
XO= -0.16560409E 01  YO=  0.81048301E-06
XO= -0.16560409E 01  YO=  0.81048301E-06
XO= -0.16560409E 01  YO=  0.81048301E-06
XO= -0.16560409E 01  YO=  0.81048301E-06
XO= -0.16560409E 01  YO=  0.81048301E-06
RIGHT SIDE OF REGION
XO=  0.23058719E 01  YO= -0.14474706E-00
QRAD=  0.14034149E-03  QRADS=  0.12585783E-02
QRDA=  0.42508919E-04  QRDAS=  0.69546331E-03

                    J= 14
LEFT SIDE OF REGION
XO=  0.22526391E 01  YO=  0.15221333E-00
MIDDLE OF REGION
XO= -0.13709121E 01  YO=  0.67093810E-06
XO= -0.18119199E 01  YO=  0.88677174E-06
XO= -0.18119199E 01  YO=  0.88677174E-06
XO= -0.18119199E 01  YO=  0.88677174E-06
XO= -0.18119199E 01  YO=  0.88677174E-06
XO= -0.18119199E 01  YO=  0.88677174E-06
RIGHT SIDE OF REGION
XO=  0.22526391E 01  YO= -0.15221333E-00
QRAD=  0.14002769E-03  QRADS=  0.13986060E-02
QRDA=  0.42259484E-04  QRDAS=  0.73772300E-03

                    J= 15
LEFT SIDE OF REGION
XO=  0.22024230E 01  YO=  0.15930393E-00
MIDDLE OF REGION
XO= -0.14795929E 01  YO=  0.72412760E-06
XO= -0.19555622E 01  YO=  0.95707173E-06
XO= -0.19555622E 01  YO=  0.95707173E-06
XO= -0.19555622E 01  YO=  0.95707173E-06
XO= -0.19555622E 01  YO=  0.95707173E-06
XO= -0.19555622E 01  YO=  0.95707173E-06
RIGHT SIDE OF REGION
XO=  0.22024230E 01  YO= -0.15930393E-00
QRAD=  0.13925465E-03  QRADS=  0.15378604E-02
QRDA=  0.41785250E-04  QRDAS=  0.77950825E-03

                    J= 16
LEFT SIDE OF REGION
XO=  0.21550063E 01  YO=  0.16607836E-00
MIDDLE OF REGION
XO= -0.15991780E 01  YO=  0.78265373E-06
XO= -0.21136165E 01  YO=  0.10344251E-05
XO= -0.21136165E 01  YO=  0.10344251E-05
XO= -0.21136165E 01  YO=  0.10344251E-05
XO= -0.21136165E 01  YO=  0.10344251E-05
XO= -0.21136165E 01  YO=  0.10344251E-05
RIGHT SIDE OF REGION
XO=  0.21550063E 01  YO= -0.16607836E-00
QRAD=  0.13812818E-03  QRADS=  0.16759888E-02
QRDA=  0.41147266E-04  QRDAS=  0.82065551E-03

                    J= 17
LEFT SIDE OF REGION
XO=  0.21101912E 01  YO=  0.17258302E-00
MIDDLE OF REGION
XO= -0.16593268E 01  YO=  0.81209117E-06
XO= -0.21031146E 01  YO=  0.10733323E-05
XO= -0.21031146E 01  YO=  0.10733323E-05
XO= -0.21031146E 01  YO=  0.10733323E-05
XO= -0.21031146E 01  YO=  0.10733323E-05
XO= -0.21031146E 01  YO=  0.10733323E-05
RIGHT SIDE OF REGION
XO=  0.21101912E 01  YO= -0.17258302E-00
QRAD=  0.13673197E-03  QRADS=  0.18127208E-02
QRDA=  0.40577153E-04  QRDAS=  0.86123267E-03
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
J= 18
LEFT SIDE OF REGION
XO= 0.20677826E 01  YO= 0.17883314E-00
MIDDLE OF REGION
XO= -0.17373792E 01  YO= 0.85029078E-06
XO= -0.22962756E 01  YO= 0.11238203E-05
XO= -0.22962756E 01  YO= 0.11238203E-05
XO= -0.22962756E 01  YO= 0.11238203E-05
XO= -0.22962756E 01  YO= 0.11239203E-05
XO= -0.22962756E 01  YO= 0.11238203E-05
RIGHT SIDE OF REGION
XO= 0.20677826E 01  YO= -0.17883314E-00
QRAD= 0.13511229E-03  QRADS= 0.19478331E-02
QRDA= 0.39679094E-04  QRDAS= 0.90091176E-03
J= 19
LEFT SIDE OF REGION
XO= 0.20276205E 01  YO= 0.18486849E-00
MIDDLE OF REGION
XO= -0.18093828E 01  YO= 0.88553005E-06
XO= -0.23614419E 01  YO= 0.11703956E-05
XO= -0.23614419E 01  YO= 0.11703956E-05
XO= -0.23614419E 01  YO= 0.11703956E-05
XO= -0.23614419E 01  YO= 0.11703956E-05
XO= -0.23614419E 01  YO= 0.11703956E-05
RIGHT SIDE OF REGION
XO= 0.20276205E 01  YO= -0.18486849E-00
QRAD= 0.13332676E-03  QRADS= 0.20811594E-02
QRDA= 0.39008957E-04  QRDAS= 0.93992072E-03
J= 20
LEFT SIDE OF REGION
XO= 0.19695578E 01  YO= 0.19072069E-00
MIDDLE OF REGION
XO= -0.18601890E 01  YO= 0.91431041E-06
XO= -0.24691655E 01  YO= 0.12084343E-05
XO= -0.24691655E 01  YO= 0.12084343E-05
XO= -0.24691655E 01  YO= 0.12084343E-05
XO= -0.24691655E 01  YO= 0.12084343E-05
XO= -0.24691655E 01  YO= 0.12084343E-05
RIGHT SIDE OF REGION
XO= 0.19695578E 01  YO= -0.19072069E-00
QRAD= 0.25485893E-03  QRADS= 0.23301894E-02
QRDA= 0.74291896E-04  QRDAS= 0.10142126E-02
J= 21
LEFT SIDE OF REGION
XO= 0.19192202E 01  YO= 0.20200061E-00
MIDDLE OF REGION
XO= -0.19766026E 01  YO= 0.96736911E-06
XO= -0.26124546E 01  YO= 0.12785614E-05
XO= -0.26124546E 01  YO= 0.12785614E-05
XO= -0.26124546E 01  YO= 0.12785614E-05
XO= -0.26124546E 01  YO= 0.12785614E-05
XO= -0.26124546E 01  YO= 0.12785614E-05
RIGHT SIDE OF REGION
XO= 0.19192202E 01  YO= -0.20200061E-00
QRAD= 0.24716284E-03  QRADS= 0.25831916E-02
QRDA= 0.71704779E-04  QRDAS= 0.10859174E-02

LEFT SIDE OF REGION
XO= 0.18657304E 01  YO= 0.21272937E-00
MIDDLE OF REGION
XO= -0.20616150E 01  YO= 0.10089750E-05
XO= -0.27248144E 01  YO= 0.13335515E-05
XO= -0.27248144E 01  YO= 0.13335515E-05
XO= -0.27248144E 01  YO= 0.13335515E-05
XO= -0.27248144E 01  YO= 0.13335515E-05
XO= -0.27248144E 01  YO= 0.13335515E-05
RIGHT SIDE OF REGION
XO= 0.18657304E 01  YO= -0.21272937E-00
QRAD= 0.23891085E-03  QRADS= 0.28220925E-02
QRDA= 0.69621027E-04  QRDAS= 0.11555384E-02
J= 23
LEFT SIDE OF REGION
XO= 0.17982185E 01  YO= 0.22297117E-00
MIDDLE OF REGION
XO= -0.21306790E 01  YO= 0.10427756E-05
XO= -0.28160958E 01  YO= 0.13782255E-05
XO= -0.28160958E 01  YO= 0.13782255E-05
XO= -0.28160958E 01  YO= 0.13782255E-05
XO= -0.28160958E 01  YO= 0.13782255E-05
XO= -0.28160958E 01  YO= 0.13782255E-05
RIGHT SIDE OF REGION
XO= 0.17982185E 01  YO= -0.22297117E-00
QRAD= 0.23052940E-03  QRADS= 0.30526219E-02
QRDA= 0.67121440E-04  QRDAS= 0.12226599E-02
J= 24
LEFT SIDE OF REGION
XO= 0.17459895E 01  YO= 0.23283357E-00
MIDDLE OF REGION
XO= -0.21785255E 01  YO= 0.10661922E-05
XO= -0.28793339E 01  YO= 0.14091749E-05
XO= -0.28793339E 01  YO= 0.14091749E-05
XO= -0.28793339E 01  YO= 0.14091749E-05
XO= -0.28793339E 01  YO= 0.14091749E-05
XO= -0.28793339E 01  YO= 0.14091749E-05
RIGHT SIDE OF REGION
XO= 0.17459895E 01  YO= -0.23283357E-00
QRAD= 0.11407532E-03  QRADS= 0.31646972E-02
QRDA= 0.33196430E-04  QRDAS= 0.12558503E-02
J= 25
LEFT SIDE OF REGION
XO= 0.17216728E 01  YO= 0.23765675E-00
MIDDLE OF REGION
XO= -0.22040725E 01  YO= 0.10786951E-05
XO= -0.29130991E 01  YO= 0.14256999E-05
XO= -0.29130991E 01  YO= 0.14256999E-05
XO= -0.29130991E 01  YO= 0.14256999E-05
XO= -0.29130991E 01  YO= 0.14256999E-05
XO= -0.29130991E 01  YO= 0.14256999E-05
RIGHT SIDE OF REGION
XO= 0.17216728E 01  YO= -0.23765675E-00
QRAD= 0.16724371E-03  QRADS= 0.33339409E-02
QRDA= 0.48402559E-04  QRDAS= 0.13042588E-02

WITH BLOCKAGE CORRECTION,THE RADIATIVE FLUX BY THE AVT. AND AVP. METHOD IS  0.33339409E-02  BTU/SEC-SQ FT
BY THE ABSORPTION METHOD, IT IS  0.13042588E-02
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
                              CHAIN (2)

                     Q BY AVT + AVP METHOD

                              FK=-0.19735E 01
                              PHI= 0.48950E-00
                                     J=  1
                              XD(J)=  0.56000E 00

BLFD=  0.10606E-00  AVTEM=  0.33161E 04  PH2O=  0.12865E-00  SSF=  0.25403E-05  FMIS=  0.29740E-02

            QRA =  0.43498E-06    QRADS=  0.43498E-06
                                     J=  2
                              XD(J)=  0.60000E 00

BLFD=  0.38526E-00  AVTEM=  0.33569E 04  PH2O=  0.13117E-00  SSF=  0.43398E-04  FMIS=  0.12041E-01

            QRA =  0.29743E-04    QRADS=  0.30178E-04
                                     J=  3
                              XD(J)=  0.70000E 00

BLFD=  0.82293E 00  AVTEM=  0.36470E 04  PH2O=  0.14865E-00  SSF=  0.16325E-03  FMIS=  0.22903E-01

            QRA =  0.23209E-03    QRADS=  0.26227E-03
                                     J=  4
                              XD(J)=  0.80000E 00

BLFD=  0.12882E 01  AVTEM=  0.33750E 04  PH2O=  0.13175E-00  SSF=  0.35853E-03  FMIS=  0.36357E-01

            QRA =  0.43860E-03    QRADS=  0.70087E-03
                                     J=  5
                              XD(J)=  0.90000E 00

BLFD=  0.17493E 01  AVTEM=  0.30482E 04  PH2O=  0.11144E-00  SSF=  0.61387E-03  FMIS=  0.48903E-01

            QRA =  0.51323E-03    QRADS=  0.12141E-02
                                     J=  6
                              XD(J)=  0.10000E 01

BLFD=  0.24066E 01  AVTEM=  0.28161E 04  PH2O=  0.96092E-01  SSF=  0.91699E-03  FMIS=  0.63385E-01

            QRA =  0.57529E-03    QRADS=  0.17894E-02
                                     J=  7
                              XD(J)=  0.11000E 01

BLFD=  0.28804E 01  AVTEM=  0.26816E 04  PH2O=  0.88034E-01  SSF=  0.12588E-02  FMIS=  0.72558E-01

            QRA =  0.61061E-03    QRADS=  0.24000E-02
                                     J=  8
                              XD(J)=  0.12000E 01

BLFD=  0.33680E 01  AVTEM=  0.25283E 04  PH2O=  0.79473E-01  SSF=  0.16320E-02  FMIS=  0.80710E-01

            QRA =  0.58595E-03    QRADS=  0.29860E-02
                                     J=  9
                              XD(J)=  0.13000E 01

BLFD=  0.40699E 01  AVTEM=  0.24049E 04  PH2O=  0.71002E-01  SSF=  0.20306E-02  FMIS=  0.90990E-01

            QRA =  0.57715E-03    QRADS=  0.35631E-02
                                     J= 10
                              XD(J)=  0.14000E 01

BLFD=  0.45971E 01  AVTEM=  0.23050E 04  PH2O=  0.65823E-01  SSF=  0.24496E-02  FMIS=  0.97302E-01

            QRA =  0.54849E-03    QRADS=  0.41116E-02
                                     J= 11
                              XD(J)=  0.15000E 01

BLFD=  0.53477E 01  AVTEM=  0.22233E 04  PH2O=  0.60893E-01  SSF=  0.28850E-02  FMIS=  0.10590E-00

            QRA =  0.53633E-03    QRADS=  0.46479E-02
                                     J= 12
                              XD(J)=  0.16000E 01

BLFD=  0.59225E 01  AVTEM=  0.21735E 04  PH2O=  0.57094E-01  SSF=  0.33331E-02  FMIS=  0.11189E-00

            QRA =  0.53274E-03    QRADS=  0.51807E-02
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
                                   J= 13
                              XD(J)=  0.17000E 01

BLED=  0.65208E 01  AVTEM=  0.21222E 04  PH2O=  0.54998E-01  SSF=  0.37910E-02  EMIS=  0.11745E-00

              QRAD=  0.51934E-03     QRADS=  0.57000E-02
                                   J= 14
                              XD(J)=  0.18000E 01

BLED=  0.73608E 01  AVTEM=  0.20699E 04  PH2O=  0.51908E-01  SSF=  0.42560E-02  EMIS=  0.12466E-00

              QRAD=  0.50665E-03     QRADS=  0.62066E-02
                                   J= 15
                              XD(J)=  0.19000E 01

BLED=  0.80154E 01  AVTEM=  0.20545E 04  PH2O=  0.51058E-01  SSF=  0.47259E-02  EMIS=  0.13047E-00

              QRAD=  0.52011E-03     QRADS=  0.67268E-02
                                   J= 16
                              XD(J)=  0.20000E 01

BLED=  0.89273E 01  AVTEM=  0.20220E 04  PH2O=  0.49105E-01  SSF=  0.51991E-02  EMIS=  0.13739E-00

              QRAD=  0.51740E-03     QRADS=  0.72442E-02
                                   J= 17
                              XD(J)=  0.21000E 01

BLED=  0.98796E 01  AVTEM=  0.20077E 04  PH2O=  0.48284E-01  SSF=  0.56736E-02  EMIS=  0.14466E-00

              QRAD=  0.53100E-03     QRADS=  0.77752E-02
                                   J= 18
                              XD(J)=  0.22000E 01

BLED=  0.10873E 02  AVTEM=  0.19965E 04  PH2O=  0.47631E-01  SSF=  0.61481E-02  EMIS=  0.15178E-00

              QRAD=  0.54486E-03     QRADS=  0.83200E-02
                                   J= 19
                              XD(J)=  0.23000E 01

BLED=  0.11416E 02  AVTEM=  0.19898E 04  PH2O=  0.47242E-01  SSF=  0.66217E-02  EMIS=  0.15543E-00

              QRAD=  0.54935E-03     QRADS=  0.88694E-02
                                   J= 20
                              XD(J)=  0.24000E 01

BLED=  0.12484E 02  AVTEM=  0.19848E 04  PH2O=  0.46950E-01  SSF=  0.75410E-02  EMIS=  0.16260E-00

              QRAD=  0.11045E-02     QRADS=  0.99739E-02
                                   J= 21
                              XD(J)=  0.26000E 01

BLED=  0.13963E 02  AVTEM=  0.19775E 04  PH2O=  0.46525E-01  SSF=  0.84485E-02  EMIS=  0.17187E-00

              QRAD=  0.11356E-02     QRADS=  0.11110E-01
                                   J= 22
                              XD(J)=  0.28000E 01

BLED=  0.15271E 02  AVTEM=  0.19722E 04  PH2O=  0.46218E-01  SSF=  0.93393E-02  EMIS=  0.17962E-00

              QRAD=  0.11526E-02     QRADS=  0.12262E-01
                                   J= 23
                              XD(J)=  0.30000E 01

BLED=  0.16665E 02  AVTEM=  0.19718E 04  PH2O=  0.46195E-01  SSF=  0.10210E-01  EMIS=  0.18767E-00

              QRAD=  0.11759E-02     QRADS=  0.13438E-01
                                   J= 24
                              XD(J)=  0.32000E 01

BLED=  0.18150E 02  AVTEM=  0.19737E 04  PH2O=  0.46307E-01  SSF=  0.10644E-01  EMIS=  0.19583E-00

              QRAD=  0.61364E-03     QRADS=  0.14052E-01
                                   J= 25
                              XD(J)=  0.33000E 01

BLED=  0.18930E 02  AVTEM=  0.20013E 04  PH2O=  0.48922E-01  SSF=  0.11280E-01  EMIS=  0.20287E-00

              QRAD=  0.98517E-03     QRADS=  0.15037E-01
                        Q BY AVT + AVP METHOD

TOTAL RADIANT HEAT FLUX IS   0.15036862E-01   BTU/SEC-SQ FT
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
                    CHAIN (3)

          HEAT FLUX BY ABSORPTION METHOD
                    J=  1
       XD(J)=  0.56000E 00

QRDA= 0.74689E-07    QRDAS= 0.74689E-07
                    J=  2
       XD(J)=  0.60000E 00

QRDA= 0.50860E-05    QRDAS= 0.51607E-05
                    J=  3
       XD(J)=  0.70000E 00

QRDA= 0.36463E-04    QRDAS= 0.41623E-04
                    J=  4
       XD(J)=  0.80000E 00

QRDA= 0.64390E-04    QRDAS= 0.10601E-03
                    J=  5
       XD(J)=  0.90000E 00

QRDA= 0.80574E-04    QRDAS= 0.18659E-03
                    J=  6
       XD(J)=  0.10000E 01

QRDA= 0.93671E-04    QRDAS= 0.28026E-03
                    J=  7
       XD(J)=  0.11000E 01

QRDA= 0.95493E-04    QRDAS= 0.37575E-03
                    J=  8
       XD(J)=  0.12000E 01

QRDA= 0.94769E-04    QRDAS= 0.47052E-03
                    J=  9
       XD(J)=  0.13000E 01

QRDA= 0.95205E-04    QRDAS= 0.56573E-03
                    J= 10
       XD(J)=  0.14000E 01

QRDA= 0.92091E-04    QRDAS= 0.65782E-03
                    J= 11
       XD(J)=  0.15000E 01

QRDA= 0.91110E-04    QRDAS= 0.74893E-03
                    J= 12
       XD(J)=  0.16000E 01

QRDA= 0.88668E-04    QRDAS= 0.83759E-03
                    J= 13
       XD(J)=  0.17000E 01

QRDA= 0.88632E-04    QRDAS= 0.92623E-03
                    J= 14
       XD(J)=  0.18000E 01

QRDA= 0.90721E-04    QRDAS= 0.10169E-02
                    J= 15
       XD(J)=  0.19000E 01

QRDA= 0.91227E-04    QRDAS= 0.11082E-02
                    J= 16
       XD(J)=  0.20000E 01

QRDA= 0.94834E-04    QRDAS= 0.12030E-02
                    J= 17
       XD(J)=  0.21000E 01

QRDA= 0.10179E-03    QRDAS= 0.13048E-02
                    J= 18
       XD(J)=  0.22000E 01

QRDA= 0.11091E-03    QRDAS= 0.14157E-02
                    J= 19
       XD(J)=  0.23000E 01

QRDA= 0.11596E-03    QRDAS= 0.15317E-02
                    J= 20
       XD(J)=  0.24000E 01

QRDA= 0.25189E-03    QRDAS= 0.17836E-02
                    J= 21
       XD(J)=  0.26000E 01

QRDA= 0.28888E-03    QRDAS= 0.20724E-02
                    J= 22
       XD(J)=  0.28000E 01

QRDA= 0.32669E-03    QRDAS= 0.23991E-02
                    J= 23
       XD(J)=  0.30000E 01

QRDA= 0.37396E-03    QRDAS= 0.27731E-02
                    J= 24
       XD(J)=  0.32000E 01

QRDA= 0.22030E-03    QRDAS= 0.29934E-02
                    J= 25
       XD(J)=  0.33000E 01

QRDA= 0.35214E-03    QRDAS= 0.33455E-02
          HEAT FLUX BY ABSORPTION METHOD
TOTAL RADIANT HEAT FLUX IS    0.33455245E-02   BTU/SEC-SQ FT
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
                         CHAIN (4)
              BLOCKAGE CORRECTION FACTORS
                         J= 1
LEFT SIDE OF REGION
XO= 0.75886518E 01   YO= 0.20282232E 01
MIDDLE OF REGION
XO= 0.75851804E 01   YO= 0.20222274E 01
RIGHT SIDE OF REGION
XO= 0.75011755E 01   YO= 0.20187571E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 2
LEFT SIDE OF REGION
XO= 0.74491021E 01   YO= 0.20248084E 01
MIDDLE OF REGION
XO= 0.74460008E 01   YO= 0.19851218E 01
RIGHT SIDE OF REGION
XO= 0.74857769E 01   YO= 0.19622639E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 3
LEFT SIDE OF REGION
XO= 0.71862355E 01   YO= 0.20167705E 01
MIDDLE OF REGION
XO= 0.71155962E 01   YO= 0.18970352E 01
RIGHT SIDE OF REGION
XO= 0.72363222E 01   YO= 0.18289298E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 4
LEFT SIDE OF REGION
XO= 0.69531841E 01   YO= 0.20147374E 01
MIDDLE OF REGION
XO= 0.68028785E 01   YO= 0.18136639E 01
RIGHT SIDE OF REGION
XO= 0.70069130E 01   YO= 0.17008278E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 5
LEFT SIDE OF REGION
XO= 0.66800777E 01   YO= 0.20083375E 01
MIDDLE OF REGION
XO= 0.65158676E 01   YO= 0.17371461E 01
RIGHT SIDE OF REGION
XO= 0.67025648E 01   YO= 0.15867960E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 6
LEFT SIDE OF REGION
XO= 0.64544933E 01   YO= 0.19988914E 01
MIDDLE OF REGION
XO= 0.62511656E 01   YO= 0.16665759E 01
RIGHT SIDE OF REGION
XO= 0.65018670E 01   YO= 0.14843652E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 7
LEFT SIDE OF REGION
XO= 0.62443291E 01   YO= 0.19881179E 01
MIDDLE OF REGION
XO= 0.60053352E 01   YO= 0.16010369E 01
RIGHT SIDE OF REGION
XO= 0.64038663E 01   YO= 0.13909550E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 8
LEFT SIDE OF REGION
XO= 0.60479786E 01   YO= 0.19766014E 01
MIDDLE OF REGION
XO= 0.57760537E 01   YO= 0.15399099E 01
RIGHT SIDE OF REGION
XO= 0.62574720E 01   YO= 0.13052168E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 9
LEFT SIDE OF REGION
XO= 0.58640474E 01   YO= 0.19649987E 01
MIDDLE OF REGION
XO= 0.55613224E 01   YO= 0.14826620E 01
RIGHT SIDE OF REGION
XO= 0.60618074E 01   YO= 0.12258724E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 10
LEFT SIDE OF REGION
XO= 0.56013869E 01   YO= 0.19534531E 01
MIDDLE OF REGION
XO= 0.53897952E 01   YO= 0.14269344E 01
RIGHT SIDE OF REGION
XO= 0.59059543E 01   YO= 0.11522011E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 11
LEFT SIDE OF REGION
XO= 0.55589732E 01   YO= 0.19422529E 01
MIDDLE OF REGION
XO= 0.51901035E 01   YO= 0.13783621E 01
RIGHT SIDE OF REGION
XO= 0.57891716E 01   YO= 0.10834363E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 12
LEFT SIDE OF REGION
XO= 0.53759314E 01   YO= 0.19313853E 01
MIDDLE OF REGION
XO= 0.49011991E 01   YO= 0.13306658E 01
RIGHT SIDE OF REGION
XO= 0.56206989E 01   YO= 0.10191351E 01
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 13
LEFT SIDE OF REGION
XO= 0.52314760E 01   YO= 0.19209437E 01
MIDDLE OF REGION
XO= 0.48921304E 01   YO= 0.12855917E 01
RIGHT SIDE OF REGION
XO= 0.54899031E 01   YO= 0.95881701E 00
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
                         J= 14
LEFT SIDE OF REGION
XO= 0.50049095E 01   YO= 0.19109638E 01
MIDDLE OF REGION
XO= 0.46620673E 01   YO= 0.12429184E 01
RIGHT SIDE OF REGION
XO= 0.53862005E 01   YO= 0.90209607E 00
QRAD= 0.             QRADS= 0.
QRDA= 0.             QRDAS= 0.
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Continued)

```
LEFT SIDE OF REGIO
XO=  0.49656097E 01  YO=  0.19014793E 01
MIDDLE OF REGION
XO=  0.45103020E 01  YO=  0.12024574E 01
RIGHT SIDE OF REGION
XO=  0.52490699E 01  YO=  0.84862743E 00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.
                 J= 16
LEFT SIDE OF REGIO
XO=  0.48430112E 01  YO=  0.18927591E 01
MIDDLE OF REGION
XO=  0.43661196E 01  YO=  0.11640180E 01
RIGHT SIDE OF REGION
XO=  0.51381540E 01  YO=  0.79791483E 00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.
                 J= 17
LEFT SIDE OF REGIO
XO=  0.47266356E 01  YO=  0.18840611E 01
MIDDLE OF REGION
XO=  0.42289710E 01  YO=  0.11274539E 01
RIGHT SIDE OF REGION
XO=  0.50326767E 01  YO=  0.75029042E 00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.
                 J= 18
LEFT SIDE OF REGIO
XO=  0.46160071E 01  YO=  0.18761410E 01
MIDDLE OF REGION
XO=  0.40983286E 01  YO=  0.10926243E 01
RIGHT SIDE OF REGION
XO=  0.49325959E 01  YO=  0.70492824E 00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.
                 J= 19
LEFT SIDE OF REGIO
XO=  0.45107235E 01  YO=  0.18687663E 01
MIDDLE OF REGION
XO=  0.39737075E 01  YO=  0.10594000E 01
RIGHT SIDE OF REGION
XO=  0.48374504E 01  YO=  0.66180626E 00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.

                 J= 20
LEFT SIDE OF REGIO
XO=  0.44104131E 01  YO=  0.18618354E 01
MIDDLE OF REGION
XO=  0.38546720E 01  YO=  0.10276649E 01
RIGHT SIDE OF REGION
XO=  0.47468689E 01  YO=  0.62081493E 00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.
                 J= 21
LEFT SIDE OF REGIO
XO=  0.42233904E 01  YO=  0.18497644E 01
MIDDLE OF REGION
XO=  0.36317123E 01  YO=  0.96822329E 00
RIGHT SIDE OF REGION
XO=  0.45784804E 01  YO=  0.54421668E 00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.
                 J= 22
LEFT SIDE OF REGIO
XO=  0.40525616E 01  YO=  0.18394075E 01
MIDDLE OF REGION
XO=  0.34270603E 01  YO=  0.91366258E 00
RIGHT SIDE OF REGION
XO=  0.44251189E 01  YO=  0.47433939E-00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.
                 J= 23
LEFT SIDE OF REGIO
XO=  0.38959210E 01  YO=  0.18305240E 01
MIDDLE OF REGION
XO=  0.32386282E 01  YO=  0.86342612E 00
RIGHT SIDE OF REGION
XO=  0.42849297E 01  YO=  0.41036059E-00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.
                 J= 24
LEFT SIDE OF REGIO
XO=  0.37517640E 01  YO=  0.18228347E 01
MIDDLE OF REGION
XO=  0.30645020E 01  YO=  0.81700365E 00
RIGHT SIDE OF REGION
XO=  0.41562980E 01  YO=  0.35163417E-00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.

                 J= 25
LEFT SIDE OF REGION
XO=  0.36839194E 01  YO=  0.18196413E 01
MIDDLE OF REGION
XO=  0.29822514E 01  YO=  0.79507545E 00
RIGHT SIDE OF REGION
XO=  0.40960303E 01  YO=  0.32387094E-00
QRAD=  0.            QRADS=  0.
QRDA=  0.            QRDAS=  0.

QRDA=  0.            QRDAS=  0.
WITH BLOCKAGE CORRECTION,THE RADIATIVE FLUX BY THE AVT. AND AVP. METHOD IS    0.          BTU/SEC-SQ FT
BY THE ABSORPTION METHOD, IT IS    0.
```

FIGURE 11. RADIATION PROGRAM, SAMPLE PRINT OUT (Concluded)

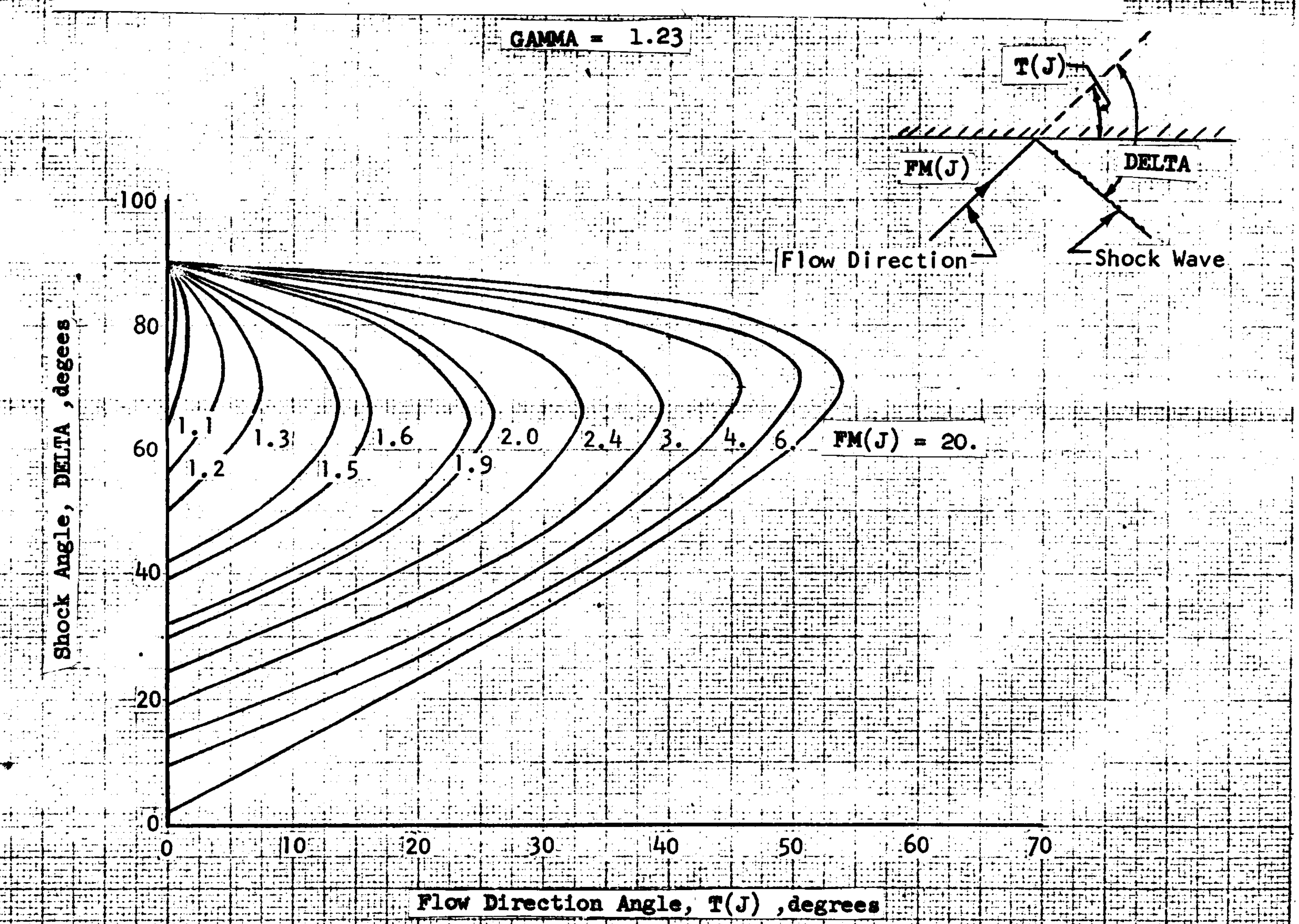


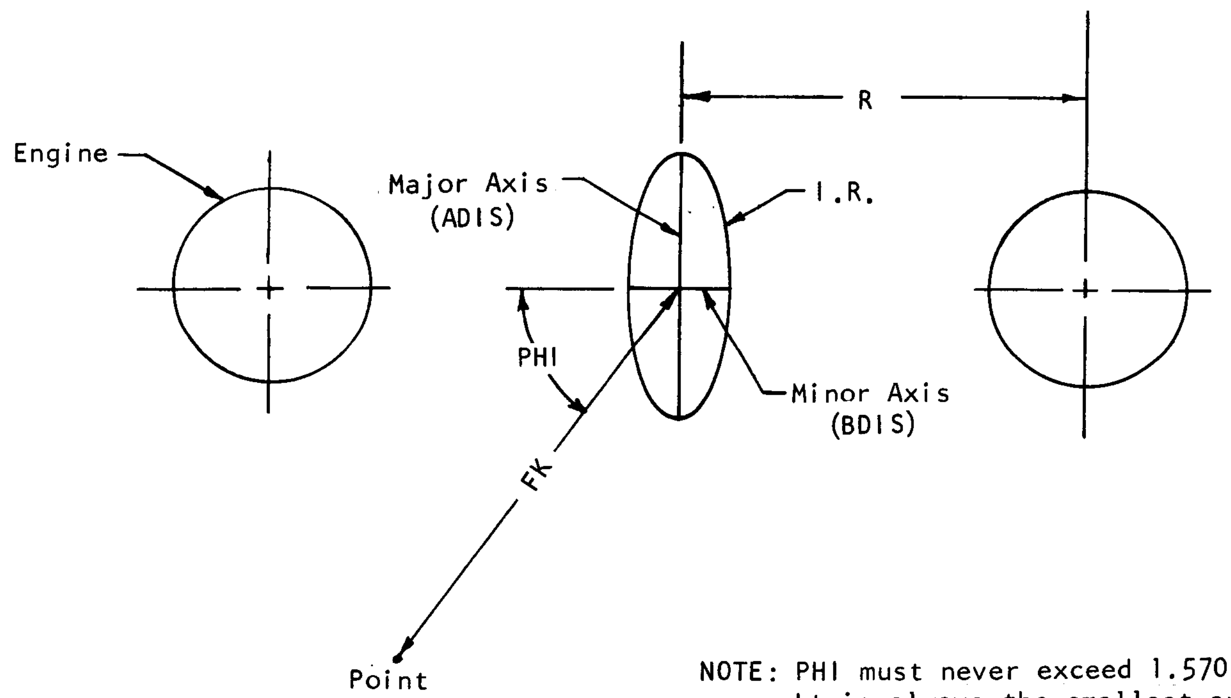
FIGURE 12. SHOCK ANGLE, DELTA, VERSUS FLOW DIRECTION, T(J), FOR SELECTED MACH NUMBERS, FM(J), USING OBLIQUE SHOCK THEORY

Mach Number (FM(J))	Theta (Radians)	Theta (Degrees)
1.1	.02827	1.62
1.4	.18325	10.5
1.6	.28796	16.5
1.8	.38045	21.8
2.0	.45724	26.2
2.4	.57417	32.9
3.0	.68935	39.5
4.0	.79232	45.4
5.0	.84293	48.3
10.0	.91972	52.7

NOTE: Values at 1.4, 1.8, 5.0, and 10.0 are interpolated from Figure 12. Notice that because of the purpose of the table our values for the maximum Theta at any given Mach number are on the low side of the actual maximum.

FIGURE 13. MAXIMUM VALUES OF THETA FOR SELECTED MACH NUMBERS

NOTE: This is a typical intersection region (I.R.). The region minor axis is on a line joining the rocket engine centers and the major axis is perpendicular to it as shown.



NOTE: PHI must never exceed 1.57079 radians. It is always the smallest angle between FK and BDIS.

FIGURE 14. GEOMETRY OF INTERSECTION REGION LOCATION

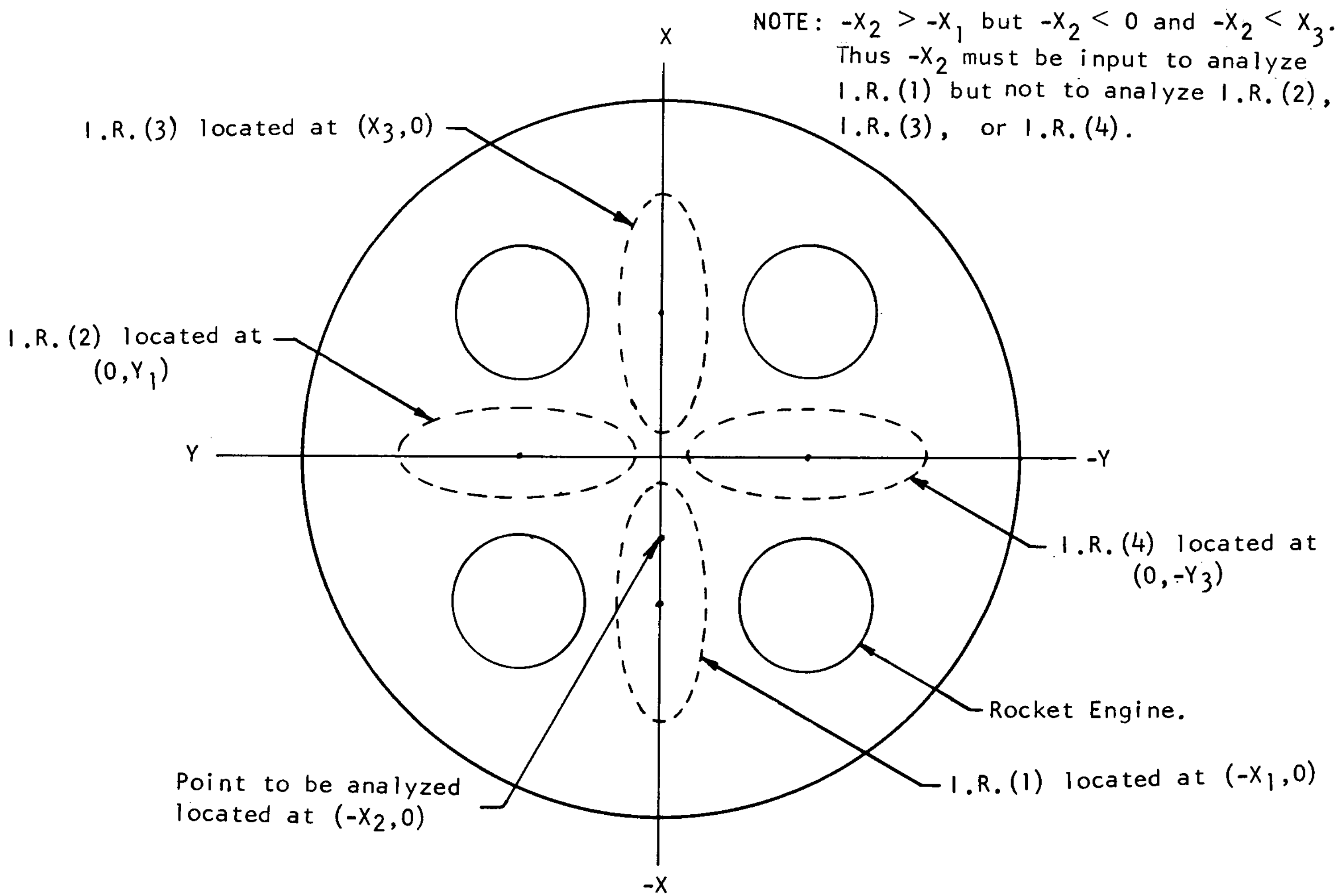


FIGURE 15. BASE GEOMETRY FOR SAMPLE PROBLEM ~ CASE IN WHICH THE X-COORDINATE MUST BE INPUT

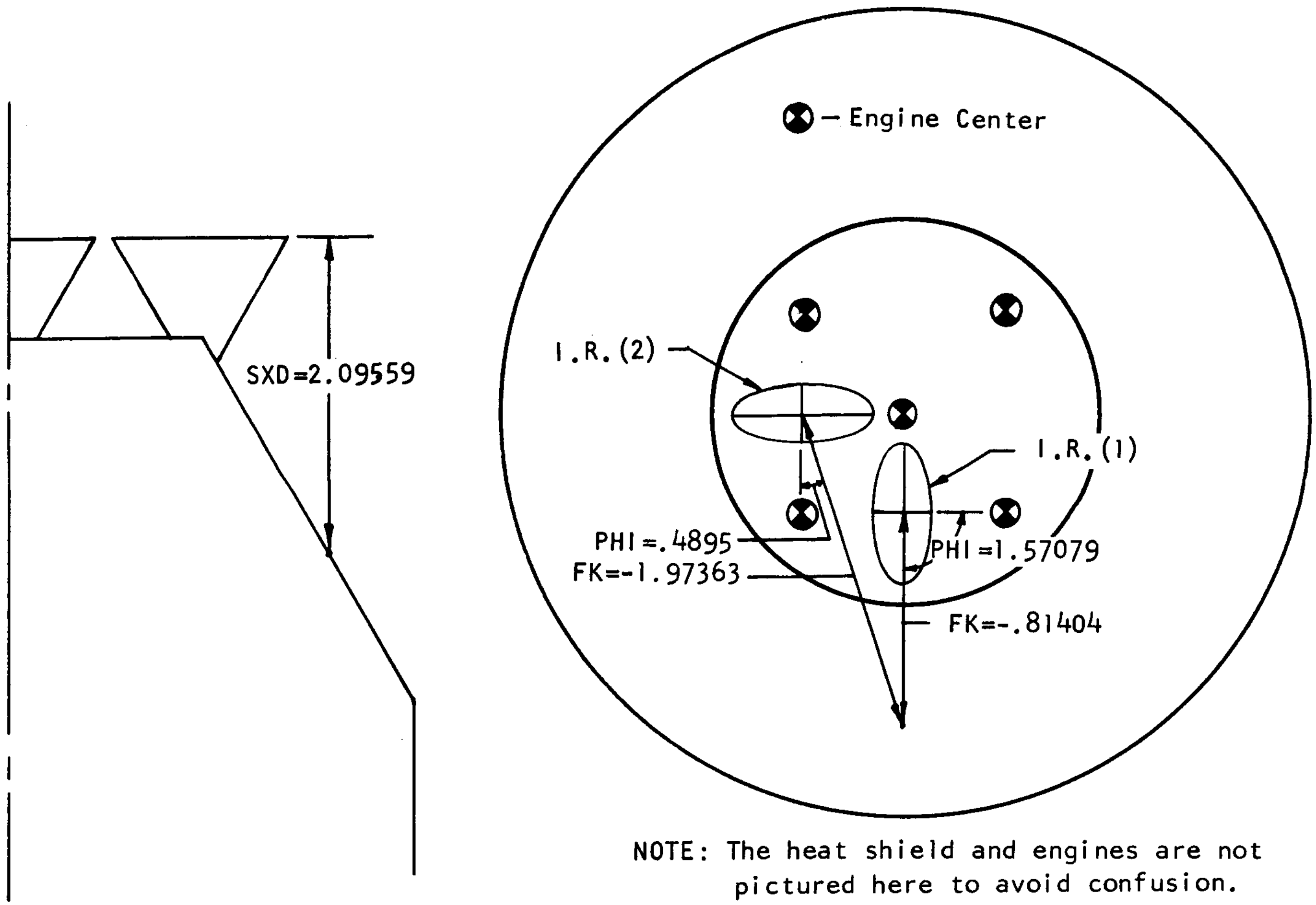


FIGURE 16. BASE GEOMETRY FOR SAMPLE PROBLEM

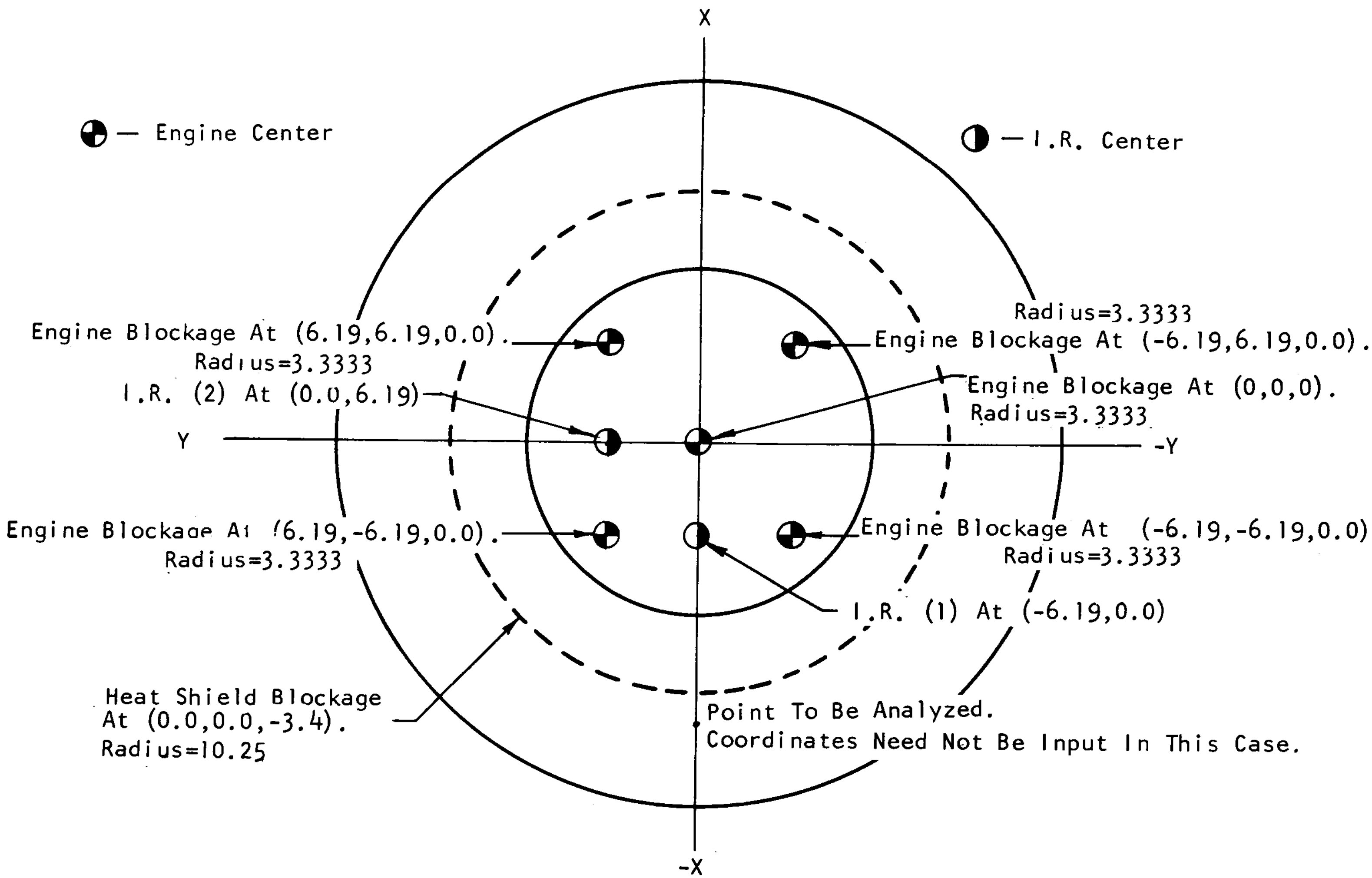


FIGURE 17. BASE GEOMETRY WITH COORDINATE LOCATIONS OF INTERSECTION AND BLOCKAGE REGIONS

CHAIN 1 INPUT

```
*Block 1   X32,X25,X+1,.92773,43.004899,5760.0,1.23*

*Block 2   .0185*

*          .55300,.60577,.66795,.75515,.82400,.87308,.91254,.96408,1.05794,1.09118*
 Block 3   1.14699,1.20885,1.27162,1.33487,1.43185,1.52983,1.68460,1.79133,1.90591*
           2.00453,2.10755,2.20516,2.31099,2.39077,2.40765,2.51795,2.6743,2.82225*
*          2.96077,3.08055,3.19207,3.35044*

*          5.55,5.678,6.121,6.027,6.01,5.89,5.874,5.840,5.80,5.78,5.75,5.723,5.715*
 Block 4   5.710,5.69,5.69,5.69,5.70,5.705,5.705,5.715,5.718,5.718,5.716,5.701*
*          5.705,5.717,5.72,5.722,5.725,5.719,5.685*

*          0.59932,0.61166,0.69823,0.65766,0.63600,0.60129,0.58471,0.56404,0.53164*
 Block 5   0.51986,0.50391,0.48549,0.46950,0.45436,0.43380,0.41471,0.38945,0.37429*
           0.36038,0.34923,0.33942,0.33107,0.32418,0.32047,0.32655,0.32794,0.31689*
*          0.30810,0.30217,0.29927,0.29961,0.31006*

*Block 6   0.932,0.971,1.022,1.062,1.103,1.131,1.156,1.182,1.242,1.260,1.292*
           1.323,1.355,1.388,1.437,1.488,1.561,1.609,1.660,1.710,1.743,1.783,1.825*
*          1.851,1.862,1.902,1.955,2.005,2.050,2.086,2.117,2.165*

*Block 7   0.56,0.60,0.70,0.80,0.90,1.00,1.10,1.20,1.30,1.40,1.50,1.60,1.70,1.80*
*          1.90,2.00,2.10,2.20,2.30,2.40,2.60,2.80,3.00,3.20,3.30*

*Block 8   1.1,1.4,1.6,1.8,2.0,2.4,3.0,4.0,5.0,10.0*

*Block 9   .02827,.18325,.28796,.38045,.45724,.57417,.68935,.79232,.84293,.91972*
```

CHAIN [illegible] INPUT

```
*Block 10  6.666,.63,3.45044*

*Block 11  -.81404,1.57079,2.09559*
```

CHAIN 4 INPUT

```
*Block 12  X6,-6.19,0.0*

*Block 13  0.0,-6.19,6.19,6.19,-6.19,0.0*

*Block 14  0.0,6.19,6.19,-6.19,-6.19,0.0*

*Block 15  -3.4,0.0,0.0,0.0,0.0,0.0*

*Block 16  10.25,3.33,3.33,3.33,3.33,3.33*

*Block 17  1.0,1.0*
```

FIGURE 18. CHAIN INPUT DATA FOR INTERSECTION REGIONS

CHAIN 2 INPUT
SECOND INTERSECTION REGION

```
*Block 10  6.666,.63,3.45044*

*Block 11  -1.97363,.4895,2.09559*
```

CHAIN 4 INPUT

```
*Block 12  X6,0.0,6.19*

*Block 13  0.0,-6.19,6.19,6.19,-6.19,0.0*

*Block 14  0.0,6.19,6.19,-6.19,-6.19,0.0*

*Block 15  -3.4,0.0,0.0,0.0,0.0,0.0*

*Block 16  10.25,3.33,3.33,3.33,3.33,3.33*

*Block 17  1.0,1.0*
```

FIGURE 18. CHAIN INPUT DATA FOR INTERSECTION REGIONS (Concluded)

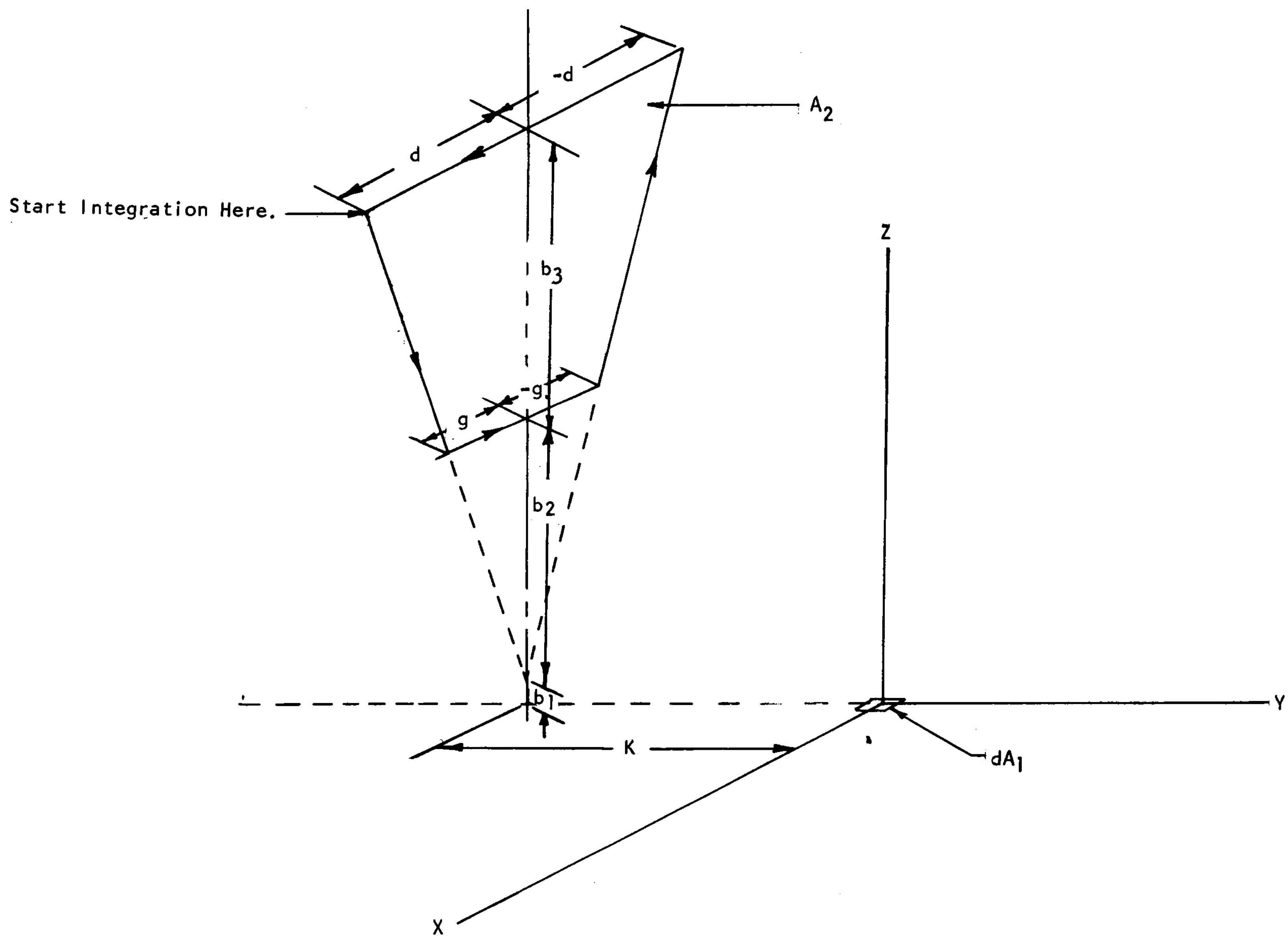


FIGURE 19. GEOMETRY OF SEGMENTED INTERSECTION REGION USED TO DETERMINE FORM FACTOR (SEE APPENDIX A)

APPENDIX A

With reference to Figure 19, the form factor F from the region to area dA_1 is given by Reference 2 to be

$$F_{dA_1 - A_2} = \oint_c \frac{(y_2 - y_1)\,dx_2 - (x_2 - x_1)\,dy_2}{2\pi r^2}. \tag{33}$$

Since A_2 is assumed parallel to the xz plane then $dy_2 = 0$ and

$$F_{dA_1 - A_2} = \oint_c \frac{(y_2 - y_1)\,dx_2}{2\pi r^2}. \tag{34}$$

By choosing dA_1 at the origin

$$y_1 = x_1 = z_1 = 0. \tag{35}$$

Then,

$$F_{dA_1 - A_2} = \frac{K}{2\pi} \oint_c \frac{dx_2}{r^2} \tag{36}$$

where

$$K = y_2. \tag{37}$$

Now the magnitude of the radius vector, r, is defined by

$$r^2 = x_2{}^2 + y_2{}^2 + z_2{}^2 = x_2{}^2 + K^2 + z_2{}^2 \tag{38}$$

but

$$z_2 = m\ x_2 + b. \tag{39}$$

Therefore,

$$r^2 = (1 + m^2)\ x_2{}^2 + (2mb)x_2 + (K^2 + b^2) \tag{40}$$

and

$$F_{dA_1-A_2} = \frac{K}{2\pi} \oint_c \frac{dx_2}{(1 + m^2)\ x_2{}^2 + (2mb)x_2 + (K^2 + b^2)}\ . \tag{41}$$

Integrating and proceeding around the trapezoid in the direction indicated yields

$$I_2 = \frac{K}{2\pi} \left(\frac{1}{\sqrt{K^2 + (b_1 + b_2)^2}}\right) \tan^{-1} \left(x \sqrt{\frac{1}{K^2 + (b_1 + b_2)^2}}\right)\Bigg]_{+g}^{-g} \tag{42}$$

$$I_4 = \frac{K}{2\pi} \left(\frac{1}{\sqrt{K^2 + (b_1 + b_2 + b_3)^2}}\right) \tan^{-1} \left(x \sqrt{\frac{1}{K^2 + (b_1 + b_2 + b_3)^2}}\right)\Bigg]_{-d}^{+d} \tag{43}$$

and

$$F_{dA_1-A_2} = I_2 + I_4. \tag{44}$$

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A FORTRAN PROGRAM TO CALCULATE THE THERMAL RADIATION TO THE BASE OF A MULTI-ENGINE SPACE VEHICLE

By E. R. Heatherly, M. J. Dash, G. R. Davidson and C. A. Rafferty

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